Soil Physical Properties and Root Growth of Radiata Pine

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy at the University of Canterbury by

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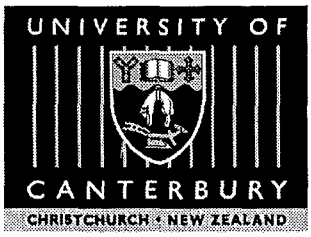

University of Canterbury

1999

STATEMENT OF ORIGINALITY

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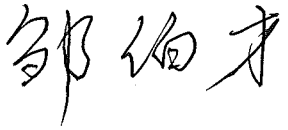

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December 6 1999

ACKNOWLEDGEMENTS

This research was carried out with the financial support of a University of Canterbury Doctoral Scholarship and a University of Canterbury internal research grant.

I wish to acknowledge and thank all the people who have helped me to carry out this research.

Firstly I wish to thank my supervisor, Professor Roger Sands (School of Forestry, University of Canterbury) for his continual encouragement and guidance throughout my whole study. His vast experience in the interface of plant and soil has been a main source to guide me through all the problems I encountered in my study. His genuine interest in and attitude to science has been an excellent example for my future career.

I also gratefully thank Dr Rabi Misra (Faculty of Science, University of the Sunshine Coast, Australia). His practical experience in plant and soil has been very precious to me. His comments on my experimental design and his help in designing the laboratory penetrometer have saved me a lot of time at the initial stage of my experiments. I thank Dr Irene Hudson (Department of Mathematics and Statistics, University of Canterbury). Irene's knowledge and skills to deal with the biological experimental data enabled me to recognise the inner relationship shadowed by the numeric data and the magic of statistic analysis in research. I give special thanks to Dr Osbert Sun (New Zealand Forest Research Limited). As a friend and also a colleague, Dr Sun has been involving in almost every stage of my research and was always available for invaluable advice. I benefited a lot from his experience and friendship.

I also thank the other members of the tree physiology and soil science group, namely: Dr Peter Clinton, Dr David Leung, Mr Putranto Nugroho, Mr Craig Penfold, Mr Insad Setiawan, Dr Euan Mason, Dr Matthias Koo, Ms Rosa Rivas, Mr Hongyuan Xu and Ms Marilyn Malecdan. Many ideas and solutions were achieved among the group meeting.

I thank the technicians in the School of Forestry, University of Canterbury. I thank Karl Schasching for organising any financial expenditure. I give special thanks to Bob Bullsmith for sorting out the psychrometer and help with the controlled growth cabinets. Paul Fuller was very kind to offer his engineering expertise to make a couple of hundred steel tubes and some specific penetrometer metal probes, and he helped sort out the problems of the air-conditioning system in the laboratory. Vicki Wilton always gladly gave assistance and organised the experimental equipment and chemicals.

I gratefully acknowledge Dr Elaine Birk from Rayonier NZ Ltd for her co-operation and interest in my research. Elaine has been very helpful in identifying the soil textures required in this study from the plantation soils of Rayonier NZ Ltd and personally travelled to Gisborne office to assist in collecting soils from the field. I also wish to express my thanks to the staff of Rayonier New Zealand Ltd, especially the Gisborne office and the former Taupo office for their assistance in collecting soil samples for my research.

Thanks to Associate Professor Graeme Buchann (Soil and Physical Sciences Group, Lincoln University) for his comments on my research project and his offering me the free access to a Tru-Psi water potential psychrometer.

I appreciate the interest and support from Proseed New Zealand Limited for providing valuable radiata pine seeds free of charge.

I thank the School of Forestry secretaries, Victoria Mackisack and Jeanette Allen for their excellent co-operation and services. They were always helpful and prepared to listen and were also willing to offer their help whenever it was needed.

Finally I would like to thank my wife Olivia Yuhui Luo for her continued support and encouragement during my time of study.

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LIST OF ABBREVIATIONS AND SYMBOLS

%	percent
ε	total porosity ($cm^3\ cm^{-3}$)
β	(Beta) curve steepness or slope
Ψ	water potential (- MPa)
Ψ_π	osmotic water potential (- MPa)
$\Psi_{\pi y}$	osmotic potential at yield turgor pressure (- MPa)
ε_a	air-filled porosity ($cm^3\ cm^{-3}$)
α	(alpha) asymptotic upper limit
ρ_b	soil bulk density ($g\ cm^{-3}$)
μm	micrometre
θ_m	gravimetric soil water content ($g\ g^{-3}$)
Ψ_m	soil matric potential (- MPa)
δ_{max}	maximum root growth pressure (MPa)
$\mu mol\ m^{-2}\ s^{-1}$	micro mole per metre squared per second
ΔR	root elongation rate ($cm\ day^{-1}$)
ρ_s	soil particle density ($g\ cm^{-3}$)
ΔS	shoot elongation rate ($cm\ day^{-1}$)
θ_v	volumetric water content ($cm^3\ cm^{-3}$)
^0C	degree Celsius
AWC	available water capacity ($cm^3\ cm^{-3}$)
cm^3	cubic centimetre
DF	degrees of freedom
e	(exponential) base number for natural logarithms =2.71828
g	gram

$g\ cm^3$	gram per cubic centimeter
KPa	kilopascal
M	mol/litre
mg	milligram
mg/l	milligram per litre
ml, µl	millilitre, microlitre
mm, cm	millimeter, centimetre
MPa	megapascal
n	number of sampling units in sample
OM	organic matter content (%)
PAR	photosynthetically active radiation ($\mu mol\ m^{-2}\ s^{-1}$)
ppm	parts per million
P_s	soil mechanical impedance to root penetration (MPa)
Pt	turgor pressure of root cell (MPa)
Q	soil strength (MPa)
R^2	coefficient of determination
R_m	root biomass (g)
RMS	residual of mean square
S.E.	standard error
S_m	shoot biomass (g)
SS	corrected total sum of squares
STD	standard deviation
v / v	volume / volume
Φ	wall yielding coefficient ($mm\ day^{-1}\ MPa^{-1}$)
Y	yield turgor (MPa)

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ABSTRACT

Soil water potential decreased exponentially and soil strength increased logarithmically as the volumetric water content decreased in soils of contrasting texture at a range of bulk densities. Soil air-filled porosity was a linear function of volumetric water content.

At constant soil strength and non-limiting soil air-filled porosity (≥ 0.16 cm^3 cm^{-3}), the root elongation rate of radiata pine seedlings decreased linearly with soil water potential in the range - 0.01 to - 0.20 MPa. The rate of decrease in elongation rate was reduced with increasing soil strength. When soil water potential was < – 0.20 MPa, the root elongation rate was linearly related to the log of negative soil water potential. The root elongation rate decreased exponentially with increase of soil strength at constant soil matric potential and non-limiting air-filled porosity. This relationship was independent of both soil water potential and soil texture. However the diameters of both root and root tip increased, but root biomass decreased with increase of soil strength.

There was no significant osmotic regulation at water potentials in the rooting media of ≥ - 0.2 MPa. Osmotic regulation commenced at < - 0.20 MPa and this partially compensated for the turgor loss from water stress. The wall yielding coefficient decreased with loss of turgor. The reduction in the root elongation rate with decreased water potential was an integrated effect of both decreased turgor pressure and reduced wall yielding coefficient. Roots osmotically regulated against increasing soil strength. No significant relationship between yield turgor pressure and both water potential and soil strength was observed.

When soil air-filled porosity was non-limiting, root elongation rate in soil (ΔR) was determined by soil matric potential (Ψ_m) and soil strength (Q) and was best described by a non-linear model: $\Delta R = \alpha\, e^{-\beta Q + \gamma \Psi m}$. The effect of water potential in decreasing root growth was most pronounced at low soil strength. Roots of radiata pine are able to penetrate higher soil strength at higher soil matric potential, and root growth of radiata pine seedlings ceased at higher soil matric potential in compacted soil than in loose soil.

CHAPTER 1

INTRODUCTION AND RATIONALE

1.1 Background

Radiata pine (*Pinus radiata* D. Don) is one of the most popular commercial plantation species in Australia and New Zealand. In New Zealand, the forestry industry is almost totally reliant on radiata pine plantations. However both in Australia and New Zealand, the productivity of the second rotation of radiata pine plantations was reported to decline (Whyte, 1973; Sands and Bowen, 1978; Dyck, 1990). This decline has been attributed, in part, to soil compaction from the first rotation harvesting (Berg, 1975; Sands and Bowen, 1978; Murphy, 1983; Mason *et al.*., 1988; Firth and Murphy, 1989; Balneaves, 1990; Zabowski *et al.*, 1994; 1996; Murphy, *et al.*, 1997). The site productivity loss from soil compaction may range between 10 - 20 % with an average of 15% where compaction occurs (Greacen and Sands, 1980).

Because forest trees with well-developed root systems are better able to take up nutrients and moisture and are more resilient to drought stress (Nambiar, 1983), the root growth capacity has been correlated with productivity (Passioura, 1994). Soil compaction confines or constrains the development of the root system (Squire, *et al.*, 1978; Squire and Flinn, 1981; Sheriff and Nambiar, 1995), and therefore results in the reduction of site productivity.

The direct result of soil compaction is an increase of bulk density. An increase of soil bulk density results in an increase of soil strength and a decrease of soil air-filled

porosity and change of soil matric potential. While increased soil strength and decreased air-filled porosity and water potential may have a detrimental effect on root growth, the interaction of these three soil physical properties in compacted soils is complicated and poorly understood.

1.2 Research Objectives

The primary aims of this research include:

(I). To investigate the interactions among soil physical properties over a range of soil bulk densities of contrasting soil textures, and to establish the relationship between soil water potential, soil strength and soil air-filled porosity and the soil volumetric water content using non-linear modelling approaches;

(II). To determine the quantitative relationship between root growth and soil matric potential at constant soil strength at non-limiting soil air-filled porosity;

(III). To determine the quantitative relationship between root growth and soil strength at constant soil matric potential and test this relationship in a range of soil textures while maintaining non-limiting soil air-filled porosity;

(IV). To investigate the physiological responses of roots to both water stress and increased soil strength;

(V). To establish a root growth model to describe the interactive effect of both soil matric potential and soil strength and simulate the root growth process in drying soil and in compacted soil.

1.3 Structure of Studies Reported in the Thesis

There are eight chapters in the thesis: six research chapters plus an introduction (Chapter 1) and a literature review (Chapter 2).

Chapter 1 is a general introduction to this project and the thesis.

Chapter 2 is a literature review. In this chapter, soil compaction is shown to be directly associated with the current harvesting methods. Site productivity reduction caused by soil compaction is of global concern, particularly in plantations. Reduction in site productivity is largely caused by root confinement in compacted soil. The relationship between root growth and the soil physical properties that are possibly changed in compacted soils is discussed. This review points out that the quantitative relationship between root growth and key soil physical properties (soil water potential, soil strength, and soil air-filled porosity) is basically unknown which therefore limits the ability to predict the long term effect of harvesting methods or regimes using modelling methods.

Chapter 3: Soil matric potential, soil strength and soil air-filled porosity are associated with soil texture, soil bulk density, and soil organic matter content. Therefore four soils of contrasting textures were collected from radiata pine plantations and their particle size distribution, particle densities, organic matter content, and nutrient status were analysed in this chapter as preliminary data for further experiments.

Chapter 4: Soil matric potential, soil strength and soil air-filled porosity are inter-related physical properties. They are functions of soil bulk density, soil water content and soil texture. Non-linear modelling approaches were applied to establish the relationship between soil matric potential and soil volumetric water content (soil moisture characteristic curve), soil strength and soil volumetric water content (soil strength characteristic curve), and soil air-filled porosity and soil volumetric water content at three bulk density levels for each soil texture.

Chapter 5: The quantitative relationship between root growth and soil matric potential was studied at two target soil strength levels while maintaining soil air-filled porosity at a non-limiting level using soils of contrasting textures. The soil matric potential was established in pressure chamber over the range - 0.01 MPa to - 0.20 MPa. Target soil strengths were 0.50 MPa and 1.50 MPa. This relationship was again tested by planting seedlings of radiata pine in PEG 4000 solution rooting medium at a wider water potential range (from - 0.01 MPa to - 1.50 MPa).

Chapter 6: The quantitative relationship between root growth and soil strength was tested in pumice soil with a matric potential of - 0.01 MPa and non-limiting air-filled porosity. Meanwhile the morphological change of root to increased soil strength was also investigated. This relationship was then tested in soils of different textures at - 0.1 MPa at non-limiting air-filled porosity.

Chapter 7: The physiological responses of roots to soil matric potential and soil strength were investigated. The changes of osmotic potential, turgor pressure, yield turgor pressure and wall yielding coefficient of root tissue in response to both decreased water potential in rooting medium and increased soil strength in soil were studied in this chapter.

Chapter 8: Radiata pines were grown in the four soil textures, at three bulk densities in each texture and with soil matric potentials ranging from - 0.01 to - 0.20 MPa. Based on the results achieved in Chapter 5 and in Chapter 6, root growth was simulated as an integrated result of soil matric potential and soil strength while soil air-filled porosity was non-limiting. A root growth model including soil matric potential and soil strength was established using non-linear modelling approaches. This model was then used to predict the root growth reduction in drying soil and in compacted soil.

CHAPTER 2

Soil Compaction and Root Growth — Literature Review

2.1 Soil Compaction and Site Productivity

Soil compaction has been widely reported to reduce the site productivity of plantations (Sands and Bowen, 1978; Froehlich *et al.*, 1984; Warkotsch *et al.*, 1994; Murphy *et al.*, 1997). Harvesting operations are the main cause of soil compaction. The site productivity of logging-compacted stands was reported to reduce by 15 - 25 % (Greacen and Sands, 1980).

2.1.1 Harvesting and Soil Compaction

Soil physical properties are among the major determinants of site productivity, and these must be protected if crop yields are to be maintained and sustainable land management objectives achieved. Since the mid-1960s, the risk of soil physical degradation by compaction in forest plantations has increased due to the greater use of heavy plant and equipment and the tendency to operate harvesting machinery in all seasons (Costantini, 1995).

Changes in soil physical properties with forest harvesting have been widely reported (Laing *et al.*, 1988; Hartge and Ellies, 1990; Lacey, 1993; Lacey *et al.*, 1994; Huang *et al.*, 1996). A recent study on *Eucalyptus regnans* forest in south-eastern Australia by Rab (1994) indicated that logging significantly increased bulk density, and decreased

organic matter content, total porosity and macroporosity on over 72% of the coupe area. On 35% of the coupe area (snig tracks, log landings and areas of disturbed subsoil) the bulk densities and macroporosities reached critical levels where tree growth could be seriously affected. Merino *et al.* (1998) and Costantini (1995) gave similar reports about compaction in radiata pine plantations.

Ground-based logging systems require the construction of landings and skid roads, which are then subject to compaction. Landings can comprise 4 - 5% of a cut-block area, and skid roads 14 - 30% (Carr, 1987; McLeod, 1988; Firth and Murphy, 1989). A combination of soil factors and the kind and magnitude of compaction forces applied determine the extent of compaction. Key factors include the amount and type of pressure and vibration applied, the number of machine passes, the nature and thickness of the forest floor, soil structure, soil texture, soil density and soil water content during the compaction activities.

Lacey (1993) reviewed the degree of soil disturbance from logging operations under a range of logging methods and characterised the soil deformation levels into two categories. The Area Exposed to Mineral Soil (AEMS) varied from 2 to 69% and Area Deep Disturbance (ADD) from 3 -58%. Ground skidding caused the maximum damage, 25% of the soil being under the damage class ADD, suggesting that yarding method may influence soil disturbance more than any single factor. Disturbance intensity varies considerably and snig-tracks and log landings usually cause the greatest damage.

Different soils respond differently to the same amount of compaction force. Soils with high levels of organic matter are generally more resilient to compaction since organic matter increases both soil elasticity and soil resistance to external force (Shepperd, 1993). The same soil will respond differently to the same amount of compaction depending on its moisture content, previous compaction depth, and the depth and nature of the protective blanket of litter over it. Dry soil is usually more resistant to compaction than wet soil and the first compaction of a previously un-compacted soil

usually has the greatest impact.

2.1.2 Soil Compaction and Site Productivity Reduction

The global literature clearly shows that soil compaction affects future site productivity (Greacen and Sands, 1980; Froehlich *et al.*, 1984; Warkotsch *et al.*, 1994; Scheerer *et al.*, 1995; Murphy *et al.*, 1997). Greacen and Sands (1980) compiled an extensive literature review of the effects of soil compaction on tree growth and found that in 142 studies reported, 117 (24 species) showed significant yield reductions, 12 (1 species) showed yield increase, 8 observed both yield reduction and increase, and 5 (1 species) found no effect on yield. They concluded that about a 15% reduction in volume yield due to compaction from tractor logging could be expected on average.

2.1.2.1 Site Productivity Reduction —A Global Concern

A reduction in productivity following soil compaction has been reported in many plantations throughout the world. The effect has been shown for a range of species, soil types, climates and regions.

Results from 23 ponderosa pine plots of 16-yr-old plantations in the Tahoe National Forest, USA gave an approximate 13% reduction in volume/hectare due to the areas of landings, skid trails and areas adjacent to skid trails (Helms and Hipkin, 1986). Froehlich *et al.* (1984) reviewed the influence of site, species and operations on potential growth loss in the Pacific Northwest and indicated that stand growth may be decreased by 5-15% from compaction.

Significant productivity reduction was also reported for Douglas fir (*Pseudotsuga menziesii*). Wert and Thomas (1981) studied the effects of tractor logging in 1947 upon the productivity of a subsequent stand and the degree and extent of residual soil compaction. They found that growth reductions in the skid roads and transition zones resulted in an overall volume loss of 11.8% for the total area. After 32 years, soil in

skid roads was still heavily compacted at depths of 20 and 30 cm (bulk density > 1.20 g cm^{-3}). However, recovery from compaction had occurred in the surface 15 cm.

Loblolly pine (*Pinus taeda*) seedling growth and survival were reduced in rutted and compacted skid trails, and site preparation and fertilisation could only partially restore site productivity (Scheerer *et al.*, 1995).

Pinus radiata D Don is one of the most intensely managed commercial plantation species. There have been several reports about the productivity reduction in this species and these will be discussed in 2.1.3

The risk to long-term site productivity depends upon the speed of recovery from compaction. Risks are low where compaction is limited to the surface soil and (or) the ameliorating effects of freezing and thawing, wetting and drying, fauna activity, and root growth are large. Deep compaction particularly poses a significant long-term risk when associated with degradation of soil structure (puddling) in warm climates with low shrink-swell soils. It is expected that the compaction effect will be ameliorated with time due to the natural processes in soil. Recovery can occur quickly as reported by Thorud and Frissel (1976) following harvesting in Minnesota. Based on 11 years data from a carefully designed experiment, Murphy *et al.* (1997) concluded that the relative growth difference between radiata pines in compacted and uncompacted plots decreases with time. However, a case study in British Columbia, Canada, showed that height growth of naturally regenerated lodgepole pine on a landing was reduced by 30 - 45% after 6 years, and after another five years, the situation became even worse, and the reduction reached approximately 60% (Carr, 1987). Froehlich *et al.* (1984) considered that differences in productivity caused by compaction following harvesting were still measurable within 30 years. Perry (1964) in North Carolina, and Greacen and Sands (1980) in Australia reported no recovery in compaction after 50 years.

2.1.2.2 Why is Site Productivity Reduced in Compacted Soils?

Soil compaction confines or constrains the development of root systems (Squire *et al.*, 1978; Squire and Flinn, 1981; Sheriff and Nambiar, 1995). Because forest trees with well-developed root systems are better able to take up nutrients and moisture and are more resilient to drought stress (Nambiar, 1983), the root growth capacity has been correlated with whole-tree productivity (Passioura, 1994).

The direct result of soil compaction is an increase of bulk density. An increase of soil bulk density results in an increase of soil strength and a decrease of soil air-filled porosity and change of soil matric potential. Increased soil strength, decreased air-filled porosity and decreased soil matric potential will all individually restrict root growth. A poor root system resulting from soil compaction will retard tree growth and therefore reduce productivity.

The effects of increased soil strength, decreased air-filled porosity and decreased soil matric potential in restricting root growth may not be equal. Clayton *et al.* (1987) studied the effects of soil compaction and displacement on tree height, diameter at breast height, and radial increment on pole-sized trees (15-20 years old) on 2 clear felling sites that had regenerated naturally to *Pinus contorta* and one site planted with *Pinus ponderosa.* Significant reductions in one or more growth attributes were associated with increased soil strength and lateral soil displacement at all three sites. After comparing the relative importance of soil matric potential and soil strength on the root elongation of *Pinus radiata* D. Don in a sandy loam soil, Davis (1984) concluded that the decrease of root growth in the compacted soil was mainly influenced by soil strength.

The water situation in compacted soil is more complicated since the total water content at field capacity may increase due to compaction in coarse soil. However, the total water content is different from available water content, and further study is needed. The influence of water on root growth in compacted soil was suggested to be associated with

soil strength, and at lower levels of soil strength, the roots were more sensitive to soil moisture deficits (Davis, 1984; Dexter, 1987).

However, Krèmer and Matthies (1997) investigated the growth of *Picea abies* and reported that it was not possible to detect any adverse effects of soil compaction on tree growth on these sites with sufficient nutrients and water. Harvesting caused organic matter removal, surface soil displacement and soil deformation (Powers *et al.*, 1990). Ballard and Will (1981) reported that removing needle litter annually for 17 years reduced volume growth of radiata pine by 12% in a pumice soil in New Zealand. Surface soil removal has a disproportionately large effect on soil fertility (Powers *et al.*, 1990) because soil organic matter and nutrients usually concentrate near the soil surface and decline rapidly with depth (Pritchett, 1979). In New Zealand, the productivity of radiata pine plantations planted on windrowed sites was reported to be significantly lower than unwindrowed sites (Ballard, 1978; Dyck and Beets, 1987). Merino *et al.* (1998) evaluated the short-term effects of different forestry practices on soil properties in 62 radiata pine plantations in northern Spain. He found that tree harvesting and intense seedbed preparation decreased the content of organic matter by 65%, total nitrogen by 65%, sulphur by 39% and exchangeable calcium by 80% in the upper layer.

Recent studies in radiata pine plantations indicated that the organic matter and surface soil removal associated with harvesting decreased the nutrient availability in the remaining soil. While soil is capable of returning to pre-disturbance conditions well within a rotation period when disturbance is limited, recovery with the highest disturbance treatment could take substantially longer (Zabowski *et al.*, 1994; 1996).

2.1.2.3 Soil Protection and Amelioration of Soil Compaction

The influence of harvesting can be avoided in some cases. This will mainly depend on choosing the most appropriate machines and soil water situation when the machines are used.

Because compaction is mainly caused by pressure from the tracking of machines, avoiding the tracking or decreasing the pressure generated from the machines will decrease the impact. In practice, walker harvesters, brushwood cushions (Schafer and Sohns, 1993), low pressure tyres (Benthaus and Matthies, 1993; Hildebrand and Wiebell, 1983), tracked skidders (Murosky and Hassan, 1988) and wide-tyre skidder operations (Rollerson, 1990) have been used to reduce soil compaction. The wide tyres displayed less severe soil disturbance, but caused more compaction area due to larger turns (Rummer and Sirois, 1984). High tractive forces and slip may contribute more to soil disturbance than does ground pressure, and it is therefore better to carry the load than to skid it (Wasterlund, 1992). High flotation tires were introduced in Canada for use in forest harvesting operations on soft ground and steep slopes to reduce soil compaction and damage (Ryans, 1986; Mellgren and Heidersdorf, 1984).

For machine operation in forests, the specific contact pressure is of decisive importance for the intensity of soil damage and duration of the recovery process. Harvesters were recommended to be restricted to a permanent network of skidding lanes, to have wide tyres or tracks, and to operate on an adequate cushion of brushwood (Hofmann, 1992).

Different soil textures will have different tolerance to the same machine forces: sand sediment can bear high pressure, whereas a moist fine sandy soil should not be loaded to more than 3 kPa if severe soil compaction is to be avoided (Wasterlund, 1989). It is very useful to work out the maximum tolerable force soil could resist based on the soil texture and the soil moisture distribution and sort out the possible machine available for operation for a given soil texture and soil moisture to reduce the soil disturbance.

Bedding, discing, chopping and ripping are the practical methods used to ameliorate soil compaction, but the best methods depend on soil type and the degree of disturbance (Gent *et al.*, 1983). As early as in 1975, a series of trials had been carried out in the Riverhead Forest in New Zealand (Berg, 1975) to assess the effects of site preparation by deep ripping, and fertiliser and herbicide treatments on the survival and early growth of second-rotation radiata pine seedlings planted on natural clay ridges and on areas

compacted by the passage of heavy machinery Results showed that ripping and superphosphate application increased height growth and survival percentage of seedlings, particularly when the treatments were combined and suggested that, in future, tractor logging should be replaced wherever possible by powered cable logging to reduce soil compaction. Mason *et al.* (1988) studied the growth of radiata pine in compacted soil using two site preparation techniques and indicated that ripping and ripping plus bedding techniques caused a significant improvement in height and diameter growth between 2 and 7 years old.

2.1.3 Productivity Reduction in Radiata Pine Plantations

Radiata pine is one of the most popular commercial plantation species, especially in the Southern Hemisphere. Both in Australia and New Zealand, reduction of productivity due to compaction has been widely reported (Whyte, 1973; Berg, 1975; Sands and Bowen, 1978; Murphy, 1983; Mason *et al.*, 1988; Firth and Murphy, 1989; Balneaves, 1990; Zabowski *et al.*, 1994; Zabowski *et al.*, 1996). In Chile, Gayoso and Schlatter (1982; 1991) reported the diameter increment and height increment of logging-compacted stands decreased by 23-30% compared with the undamaged site for 4 - 6 year old radiata pine. In Spain, Merino *et al.* (1998) indicated the same problem of productivity reduction of second rotation of radiata pine in compacted soil.

2.1.4 Predicting the Long-term Effect of Compaction - Computer Model

Second rotation productivity decline from soil compaction is widely reported. However the reduction depends on soil type, harvesting method, land preparation and tree species. Productivity is controlled by a range of environmental factors over and between long rotations (20 years plus). The traditional permanent plot methods are difficult to meet the industrial interests on precise prediction of the long-term effects of different harvesting methods or land treatments on site productivity. Modelling and sophisticated computer programmes will be required to achieve this. In the past two decades, considerable emphasis has been placed on developing computer models that

can be used to predict effects of management practices on long-term forest productivity (Pastor, 1985; Kimmins, 1988; Stewart *et al.*, 1988). Stewart *et al.* (1988) in Oregon State University developed a computer program to assess the effect of compaction on productivity under different harvest specifications (e.g. vehicle type, skid trail spacing, yarding practices) of Douglas fir (*Pseudotsuga menziesii*) stands on the US west coast. Computer modelling of the long-term impact of compaction is a large step from realising the problem to estimating this problem. This will eventually lead to achieving a practical measure to handle this problem. The model developed by Stewart *et al.* (1988) was based on specifications of harvesting. The effect of the same harvest specification may have significantly different results if the soil type is different and this model tends to be restricted to a certain soil type and climate area. The challenge is to produce a model that is independent of soil type and climate and one that uses those basic soil physical factors that are affected by compaction and which control root growth. The primary reason for the productivity reduction is due to some combination of an increase of soil strength, a decrease of air-filled porosity and a change of water availability. Using these primary soil physical factors offers the opportunity to develop a more advanced and sophisticated model that includes soil water, soil aeration, soil strength and soil organic matter as independent variables to predict root growth and site productivity (Sands, 1996, personal communication). The advantage of such a model would be its ability to cope with different harvesting regimes, soil types and climate. It would have the potential to be widely applied over a range of soils and climates to evaluate the effects of a range of harvesting and management practices on future site productivity.

2.2 Soil Physical Properties in Compacted Soils

2.2.1 Bulk Density*

Soil compaction reduces soil porosity through the partial expulsion of either the permeating solution or air from the compressing soil body, or both. Application of pressure to soil will result in first the expulsion of air and is represented as the sacrifice of macropores and an increase in soil bulk density. Because soil bulk density is an easily measured index of soil compaction, studies of compaction often refer to alterations in soil bulk density.

The compaction degree is usually described in two ways. One is the percentage of bulk density increase. This is a relative value to the undisturbed soil at the same site. This value gives a very immediate feeling of the compaction degree. The other way to describe the compaction degree is using the absolute value of bulk density. Because the absolute value of bulk density is soil type and site specific (it depends on the texture, particle density and the organic matter content), this value is always associated with a certain region and certain soil type to make meaningful comparison.

In the mid-1950s, harvesting machines were mainly small size tractors and compaction was small. Steinbrenner *et al.* (1955) reported a soil bulk density increase by 2.4% in tractor-logged area and 15% in tractor roads in the southwestern Washington. Since the 1970s the use of heavy machines has greatly increased the compaction degree. Compaction was reported to increase the bulk density of the surface soil layer (0 - 10 cm) in the range of 15 - 60% for skid-roads (Dickerson, 1976; Carr, 1987) and 25 - 88% for landings (Carr, 1987; Brais and Camire, 1998).

Although the increase of bulk density does lessen with depth, a bulk density increase has been observed frequently to exist at depths of 30 cm or more (Froehlich, 1979; Wert

* Bulk denisty refers to dry bulk density and is the ratio of the mass of dry soil to the total volume of soil

and Thomas, 1981; Gent *et al.*, 1983; Carr, 1987). The increase of bulk density then causes the change of related soil physical properties (Dickerson, 1976; Gent *et al.* 1983; Carr, 1987).

The duration of these bulk density increases is an important consideration as well. Thorud and Frissel (1976) found that compaction longevity might be less than 10 years at the soil surface. Other authors have reported that compaction effects can persist for a period of longer than 30 years at all depths examined (Sands *et al.*, 1979; Wert and Thomas, 1981; Jakobson and Greacen, 1985; Murphy *et al.*, 1997).

For a given compaction force, the resulting bulk density is a function of soil moisture. Typically a dry soil can better resist compaction. As soil wetness increases, the moisture films weaken the inter-particle bonds and reduce internal friction, thus making the soil more compactible (Leaming, 1986).

Puddling can occur when soils at high water contents are compacted, the results of which are often a platy structure and a loss of air or water exchange capacity. Root channels and other pathways in the soil are important for water infiltration and movement. Compaction and puddling eliminate these channels, and thus reduce the rate of infiltration and subsurface flow. On some sites, however, water retention may be increased as soil density increases (Greacen and Sands, 1980). Water retention may also increase in compacted sandy soils, decrease in compacted loamy soils and either decrease or increase in compacted clay soils (Froehlich *et al.*, 1984).

Many papers report negative relationships between the bulk density and site productivity (Carr, 1985; Froehlich *et al.* 1986; Helms and Hipkin, 1986). However the relative impact of a unit increase in bulk density is bound to vary from soil to soil (Powers *et al.*, 1990). The critical bulk density reported to restrict plant growth differs between tree species (Gent *et al.*, 1983).

Bulk density has been used to describe the compaction degree for a long time, and it may still be used in future simply because it is easily measured. However, bulk density is not directly associated with plant physiological processes: its effect on plant growth is through its modification of soil strength, soil aeration and soil water status. Meanwhile bulk density must be related to soil texture and moisture to make meaningful comparisons. For example a coarse sandy soil with a higher bulk density may have higher air-filled porosity than in a fine texture clay soil with a lower bulk density. The soil strength of two soils with the same bulk density may differ greatly depending on the soil texture, soil organic matter and soil water content.

2.2.2 Soil Water Content and Matric Potential

The two parameters describing the soil moisture environment are soil water content by weight or by volume, and soil water potential. From the viewpoint of plant physiology, soil water potential is the ideal parameter to describe the water environment as it clearly represents the degree of available water for plant extraction. Because it is difficult to measure water potential *in situ*, soil water contents are more frequently used than soil water potentials. Both gravimetric and volumetric water content can be easily measured. Since the compaction process is a process of reduction of total porosity, the volumetric water content change will be discussed here as a result of soil compaction.

When soil is compacted, the total porosity is reduced at the expense of macropores. Because micropores are relatively less affected, the proportion of micropores is increased. The increased proportion of micropores makes the soil behave as if it were of finer texture (Greacen and Sands, 1980) and the soil volumetric water content will increase. Donnelly and Shane (1986) found that compacted loamy sand had higher soil water content than uncompacted soil. Because compaction increases soil volumetric water content, it might be assumed that compaction will increase the water available to plant roots. This inference should be used with care for the following reasons:

1). With continued compaction a point will be reached where the reduction in total porosity exceeds the increase in the proportion of micropores, after which the volumetric water content at field capacity becomes less due to the sacrifice of even the middle size pores;

2). The soil water characteristic curve largely depends on the soil texture. A greater increase in volumetric water content is expected in coarse-texture soil than in fine-texture soil.

3). The soil water characteristic curve also largely depends on the soil bulk density. Compaction increases the bulk density and therefore also changes the volumetric water content both at field capacity and wilting point. If soil water availability is defined as the water amount held between field capacity and wilting (Hanks, 1992), then available water capacity might increase, remain the same or decrease depending on the compaction degree and the soil texture.

The number of medium-sized pores, which hold most of the water easily taken up by roots, is also affected by compaction. Moderate compaction often reduces soil water availability in clay and silt soils and increases soil water availability in sandy soils. However, severe compaction will decrease the amount of soil water availability even in very coarse soils (Purser and Cundy, 1992; Woodward, 1996). The distribution of large, medium and fine pores is critical. A soil can continue to be degraded with increasing passes of a skidder, because of changes in the distribution of pores of varying sizes, even though the total volume of pores (usually calculated from bulk density), may not change (Lenhard, 1986).

2.2.3 Pore Size Distribution

The volume percentage of the total bulk of soil not occupied by solid particles is commonly called porosity (ε) and is defined as:

ε = volume of pores / total volume of soil

$$= \frac{(Vw + Va)}{(Vs + Vw + Va)}$$

$$= \theta + \varepsilon_a = 1 - \frac{\rho b}{\rho s} \quad \text{(McLaren and Cameron, 1996)} \qquad (2.1)$$

where Vw = volume of water

Va = volume of gas

Vs = volume of soil

θ = volumetric water content ($cm^3\ cm^{-3}$)

ρ_b = dry bulk density ($g\ cm^{-3}$)

ρ_s = particle density ($g\ cm^{-3}$)

The availability and transport of the soil solution and soil air are not so much dependent on the porosity but on the pore size distribution. According to Glinski and Lipiec (1990), these three types of pores are defined based on the diameter at the narrowest point:

macropores > 100 μm

mesopores 30 - 100 μm

micropores < 30 μm

Macroporosity: The degree of macroporosity sacrifice from compaction largely depends on the soil texture, compaction method and compaction degree. Studies from tropical forests showed that soil compaction from a crawler tractor can cause a reduction of 21.2% of macroporosity in tracks, and 14% for log-disturbed areas (Jusoff, 1988). A 68% macroporosity reduction was reported for wheel-rutted soils and 38% for long-disturbed soils on loamy sand to silty loam soil (Dickerson, 1976).

Both compaction and rutting start with the immediate sacrifice of macropores, and soils with high macroporosity (good aeration status and good drainage) experience the greater compaction changes (Aust, *et al.*, 1995).

Microporosity: The change of microporosity after compaction is relatively complicated. Increases in microporosity from compaction have been reported ranging between 7% in skidding trails in a silt clay loam soil (Dickerson, 1976) to 80% at a tropical forest site (Jusoff, 1988).

Total porosity: Both the decrease of macroporosity and the increase of microporosity contribute to the total porosity, and the results are usually observed as a decrease of total porosity. Reductions of 20.4% and 13.4% in total porosity have been reported in track soils and log-disturbed soils compared to undisturbed soil in tropical forests (Jusoff, 1988).

2.2.4 Soil Aeration

Soil must be adequately aerated so that gas exchange can take place between the soil and atmosphere at such a rate as to prevent a deficiency in oxygen (O_2) or an excess of carbon dioxide (CO_2) developing in the root zone (Hillel, 1980). Gas exchange in the air phase is far more efficient than in the water phase, and therefore the rates of oxygen diffusion into and CO_2 release from the root zone are largely dependent on the fraction of air-space in the soil porosity (Kramer and Byer, 1995). The air-filled porosity of a soil is defined as the ratio of the volume of air to the total volume of soil and is determined by total soil porosity and the volumetric water content (Glinski and Lipiec, 1990):

$$\varepsilon_a = \varepsilon - \theta \qquad (2.2)$$

where ε_a ($cm^3\ cm^{-3}$) is the air-filled porosity, ε ($cm^3\ cm^{-3}$) is the total porosity and θ ($cm^3\ cm^{-3}$) is the soil volumetric water content. For convenience, ε_a is often calculated

when the soil is at field capacity (McLaren and Cameron, 1996).

Compaction decreases the air-filled porosity by lowering the total porosity and changing the soil volumetric water content. Compaction decreased the total porosity mainly by reducing the number (volume) and continuity of large pores (Rab, 1994; Woodward, 1996; Martins *et al.,* 1998). It is found that an air-filled porosity as high as 0.235 cm^3 cm^{-3} in undisturbed soil could be reduced to 0.055 - 0.073 cm^3 cm^{-3} in snig-tracks and log-landing soils (Lenhard, 1986). The air-filled porosity of compacted soil was reported to be reduced to less than 0.10 cm^3 cm^{-3} over a range of soil textures and harvesting methods (Herbauts *et al.*, 1996 and 1998; Huang *et al.*, 1996; Incerti *et al.*, 1987; Jusoff, 1988).

2.2.5 Soil Strength

Soil strength is defined as the ability of soil to resist a force without shearing (McLaren and Cameron, 1990). The shear strength of a soil is derived from a combination of its cohesive strength (i.e: bonding between particles) and its internal friction (i.e. friction which occurs when particle surfaces are forced to slide over each other).

Because soil strength is highly influenced by soil bulk density, a change in soil bulk density due to soil compaction will greatly affect soil strength. The relationship between soil bulk density and soil strength was initially given by Stephens *et al.* (1941) in a pasture soil. The soil strength increased sharply with the increase of soil bulk density. Sands *et al.* (1979) used a penetrometer to measure the soil strength in radiata pine plantations and indicated that the soil strength was directly related to the bulk density, and that root growth was severely restricted at high soil strength. This raised wide concern about the detrimental impact of modern harvesting methods on site productivity. Other studies on harvesting impacts on soil physical properties and the potential influence on root growth and productivity have since been carried out (Davis *et al.*, 1984; Jakobsen and Greacen, 1985; Murosky and Hassan, 1988; Theodorou *et al.*, 1991; Lacey, 1993; Warkotsch *et al.*, 1994; Simcock, *et al.* 1995; Misra and Gibbons,

1996; Costantini *et al.*, 1996b; Smith, *et al.*, 1997; Seixas and McDonald, 1997; Stone *at al.*, 1998; Brais and Camire, 1998; Hassan and Roise, 1998). These will be discussed in detail in section 2.3.3 (Soil strength and root growth).

2.2.6 Hydraulic Conductivity

The hydraulic conductivity of a soil is the rate of discharge or flow of water through a unit cross-sectional area of soil. It is dependent on the nature of the soil pore system, including pore sizes and pore volume. Soil compaction directly reduces soil porosity and seriously degrades the pore system (see 2.2.3 and 2.2.4). Therefore compaction will change soil hydraulic conductivity.

Compaction usually reduces infiltration rate and saturated hydraulic conductivity (Greacen and Sands, 1980; Gent *et al.,* 1983; Incerti *et al.*, 1987; Rab, 1994; Huang, *et al.*, 1996). Rab (1994) reported that logging significantly reduced the saturated hydraulic conductivity in general logging areas, skid trails and log landings.

The reduction in unsaturated hydraulic conductivity is less marked than that of saturated conductivity, and there may even be an increase in unsaturated hydraulic conductivity (Sands *et al.*, 1979). Steinbrenner (1955) investigated the effect of tractor logging on physical properties of some forest soils in south-western Washington, and indicated that tractor-logged cut-overs had a 35% loss in infiltration rate and 93% loss in permeability in the tractor roads which occupied 26% of the logged area. Initial infiltration rates on disturbed sites showed a 40% reduction on several logged sites on glacial till soils with surface layers of volcanic ash-influenced loess, compared to those on undisturbed sites (Kuennen, 1979). Donnelly and Shane (1986) simulated the effect of intensive recreation and/or vehicular traffic in harvesting operations on soil infiltration within a *Quercus* forest on loamy sand in Canada and concluded that soil infiltration capacity was 3 - 5 times greater in the control plots than the compacted plots.

2.3 Root Growth - Principles and Processes

2.3.1 Root Elongation Model

A typical young root consists of a growing tip, behind which are the meristem cells which later differentiate into the cells forming the epidermis, the cortex and the stele. During differentiation the cells increase in size and elongate to push the root through the soil. The most rapid cell division area is immediately after the root cap, with a length of about 200-250 μm. Immediately after this cell division zone is the most rapid elongation zone. This zone is also small with a length of around 250 - 300 μm. Both the division and elongation processes mainly occur within 500 μm of the root tip (Kramer, 1983).

The zone of maximum root elongation varies between species. In maize, growth accelerates, reaching a maximum at 5 mm from the root cap apex, and slows over the region 5 – 10 mm from the tip, ceasing at around 10 mm from the tip (Pritchard *et al.*, 1993). Halter (1997) found that the zone of elongation in roots of *Eucalyptus nitens* (Deane and Maiden) Maiden and *Eucalyptus pauciflora* Sieber ex Sprengel subsp. *pauciflora* was largely confined to 100 to 300 μm from the root tip. In radiata pine, the most rapid cell division zone was reported within 200 μm immediately after the root tip, and the most rapid elongation zone was between 200 and 450 μm from the root tip (Youngman, 1998).

The enlargement of plant cells results from two interdependent physical processes: water absorption and cell wall yielding. Water absorption increases the volume of growing cells (which typically consist of 85% - 95% water), whereas wall yielding generates the driving force for water uptake (Cosgrove, 1986). Since wall stress and turgor pressure constitute equal and opposite forces, turgor pressure and wall stress decrease simultaneously. Such relaxation reduces the cell water potential and gives rise

to a passive water influx, which in turn increases cell volume and extends the cell wall (Cosgrove, 1986).

Growth occurs when the turgor pressure inside the elongation cells is sufficient to overcome the constraint imposed by the cell walls and any external constraint caused by the soil matrix (Green 1968; Bradford and Hsiao, 1982). The initial effect of water stress on root elongation is physical and mediated by changes in turgor pressure in the root. According to the hydraulic cell growth model developed by Lockhart (1965), a model for root elongation in soil was given by Sands (1983):

$$\Delta R = \Phi (P_t - Y - P_s) \quad \text{for } P_t > (Y + P_s) \tag{2.3}$$

where ΔR is the root elongation rate, P_t is cell turgor pressure, Y is the yield turgor, P_s is soil mechanical impedance and Φ is the wall yielding coefficient

Sands (1983) called Φ cell wall extensibility. However, Φ has been used loosely in the literature to refer to many other quantities that are quite different from Φ, e.g. elastic extensibility, Instron extensibility and plastic extensibility (Cosgrove, 1986). For this reason, the term wall yielding coefficient will be used here and later rather than cell wall extensibility to reflect the apparent dependence of wall expansion on turgor pressure.

The above model was modified by Yau and Sands (1992) as 2.4:

$$\Delta R = \Phi (\Psi - \Psi_\pi - Y - P_s) \quad \text{for } \Psi_\pi < (\Psi + Y + P_s) \tag{2.4}$$

where Ψ is the total water potential of the protoplast of the root elongation cells and Ψ_π is the osmotic potential of the protoplast of root elongation cells.

In non-saline soils, soil osmotic potential is negligible and the matric potential (Ψ_m) is approximately equal to the total water potential of the soil. Except in dryer coarse soils the water potential of the soil will be approximately equal to the water potential of the root. Therefore for the purpose of modelling it is assumed that

$$\Psi = \Psi_m \tag{2.5}$$

$$\Delta Lr / \Delta t = \Phi (\Psi_m - \Psi_\pi - Y - P_s) \quad \text{for } \Psi_\pi < (\Psi + Y + P_s) \tag{2.6}$$

According to the model of Yau and Sands (1992), increase of soil matric potential will increase the total potential of root cell and therefore increase the turgor pressure. Providing other cell properties are independent of the soil matric potential and soil mechanical impedance, turgor pressure is linearly related to soil matric potential. A possible deduction is that soil matric potential is linearly related to root growth once the turgor pressure exceeds the yield turgor.

Practical application of this model will largely depend on the understanding of the interaction of all the factors included in the model. Unfortunately the interaction among these factors in roots is largely unknown. However research on the interaction of these factors in leaves may assist in understanding how these factors interact in roots.

2.3.2 Physiological Responses of Roots to Water Stress and Soil Strength

The root growth model given by Yau and Sands (1992) is just a highly simplified description of root growth in the short term. This primary process of wall expansion and water absorption will induce complicated physiological responses (secondary processes), including osmotic regulation, change of yield turgor and wall yielding coefficient (Cosgrove *et al.*, 1984; Cosgrove, 1985; Boyer *et al.*, 1985;Van Volkenburgh and Cleland, 1986; Taylor and Davies, 1986a; 1986b). The secondary processes are essential to maintain root growth. Otherwise growth would soon cease as turgor pressure falls to yield turgor.

2.3.2.1 Wall Yielding Coefficient (Φ)

The wall yielding coefficient is high in fast growing young leaves and low in old leaves (Roden *et al.*, 1990; Taylor, *et al.*, 1992). As growth ceases, the wall yielding coefficient declines to very low values (Frost, *et al.*, 1991). The wall yielding coefficient may increase by the production of hormones but the mechanism of this regulation is only partially understood.

Water stress can cause a regulatory reduction of the wall yielding coefficient and, in this way, adapts the water requirements for growth to the availability of water in the plant. The cell wall of the stressed plants may become less elastic (Peltier and Marigo, 1996). Roden *et al.* (1990) reported that the wall yielding coefficient of leaves in un-irrigated trees was lower than that in irrigated trees. This suggests that change in the wall yielding coefficient is associated with water stress.

The wall yielding coefficient was also reported to increase in elevated CO_2 concentrations in the atmosphere (Taylor *et al.*, 1994; Gardner *et al.*, 1995). The wall yielding coefficient of hypoxia-treated plants was lower than that of aerated plants and it was suggested that leaf growth of hypoxia-stressed plants is limited by the wall yielding coefficient (Smith, 1989).

The wall yielding coefficient of leaves was reported to be associated with photon flux density (MacDonald *et al.*, 1992) and the wall yielding coefficient of leaves exposed to light was greater than in the dark (Van Volkenburgh and Cleland, 1981; Taylor and Davies, 1986a). Roots grow in the dark but this does not necessarily mean that there could not be a light-induced change in the wall yielding coefficient of roots. This will depend on whether the effect is a direct effect of light at site or a secondary effect associated with assimilate production and partitioning.

Plant growth regulators could affect wall yielding coefficient by influencing any one or combination of the factors regulating plastic cell expansion (yield threshold, wall

yielding coefficient or turgor pressure). The strongest influence of growth regulators on cell wall expansion is their impact on the wall yielding coefficient. In higher plants, auxins can increase the wall yielding coefficient(Cleland, 1981). Cytokinins and gibberellins can also increase the wall yielding coefficient and perhaps lower yield thresholds in certain sensitive tissues (Cleland, 1981). Calcium and hydrogen ions are two possible cell wall loosening factors that have been identified. An increase in the H^+ concentration and a decrease in the Ca^{2+} concentration in the wall increase the wall yielding coefficient (Nilsen and Orcutt, 1996). Both of these two cell wall loosening factors relate to the quantity and strength of hydrogen bonding between the pectin and cellulose microfibrils (Nilsen and Orcutt, 1996).

2.3.2.2 Yield Turgor

Yield turgor is defined as that turgor below which no cell expansion occurs and above which cell expansion commences (Sands *et al.*, 1992).

More recent studies show that it is likely that yield turgor pressure is under metabolic control and that water deficit might trigger a change in yield turgor (Cosgrove *et al.*, 1984; Cosgrove, 1985; Boyer *et al.*, 1985; Van Volkenburgh and Cleland, 1986). Soil drying of several days may result in a small increase in the yield turgor of leaves (Taylor and Davies, 1986b). Randall and Sinclair (1989) determined yield turgor by stress relaxation of leaf samples in a psychrometer chamber and calculated consistently low values of yield turgor (0.2 – 0.3 MPa) throughout the day in young growing leaves of soybean. MacDonald *et al.* (1992) determined the yield turgor of willow leaves (*Salix viminalis*) by using the osmotic-solution technique (Sands *et al.* 1992) and found the average yield turgor was about 0.53 MPa and suggested there was no evidence of diurnal variation in yield turgor. Taylor and Davies (1986b) found no difference in yield turgor between light and dark periods in growing leaves of birch or sycamore grown at constant air temperature. However, Halter et al. (1996) found the yield turgor in roots of *Eucalyptus pauciflora* was greater during the night (0.32 MPa) than during

the day (0.11MPa). A compensating change in yield turgor associated with changes in turgor pressure was reported by Green *et al.* (1971).

The values of yield turgor for plant tissues appear to lie in the range of 0.2 to 0.6 MPa, and seem to be adjustable under some conditions (Cosgrove, 1986; MacDonald *et al.*, 1992).

2.3.2.3 Osmotic Potential Maintenance and Osmotic Regulation

Maintaining a suitable intracellular osmotic pressure is essential for growth. Water absorption during cell expansion tends to dilute the solutes within the cells. If this proceeded unabated, growth would soon cease as turgor pressure is balanced by cell wall tension and mechanical impedance from soil. The study shows that the osmotic potential in maize roots remains constant during growth (Hsiao, *et al.*, 1985). Studies of the growth of excised oat coleoptiles indicated that solute uptake from the medium is controlled by a complex interaction between growth rate, solute availability, and maximum internal solute concentration (Stevenson and Cleland, 1981; 1982).

When plants undergo mild water stress, cell expansion is inhibited but cell solutes begin to accumulate. This is viewed as an osmotic regulation response by plants to maintain turgor pressure (Steponkus *et al.*, 1980; Bradford and Hsiao, 1982; Hsiao *et al.*, 1985). In some cases solute accumulation during water stress was reported to maintain a high turgor pressure in spite of reduced water potential (Hsiao *et al.*, 1985; Michelena and Boyer, 1982; Van Volkenburgh and Boyer, 1985; Nguyen and Lamant, 1989).

There are very few reports about osmotic regulation against increased strength. Yau and Sands (1992) studied the elongation rate of Dutch elm (*Ulmus hollandica* Mill.) root suckers in a range of soil strengths and demonstrated osmotic regulation against increasing soil strength. There is still much to be learned about the mechanism and processes of osmotic regulation in roots.

2.3.2.4 Turgor Presssure and Effective Turgor Pressure

According to the root growth model (Equation 2.4), the rate of wall expansion depends on turgor pressure. A number of studies supported this notion (Boyer, 1968; Cleland, 1981; Hsiao, *et al.*, 1985).

If wall expansion is driven by turgor pressure in excess of Y, then we can define this force as effective turgor pressure (ΔP):

$$\Delta P = Pt - Y \tag{2.7}$$

Effective turgor pressure was reported to be as small as 0.02 MPa in Nitella (Green *et al.*, 1971), but values between 0.10 - 0.30 MPa are more usual (Cosgrove, 1985; Hsiao *et al.*, 1985) and might be as large as 0.9 MPa (Milburn, 1979). However most of these studies are in leaves.

For roots, the effective turgor pressure must be able to overcome the mechanical impedance from soil in order for roots to elongate, and therefore the effective turgor pressure in roots must be high compared to the effective turgor pressures in leaves in order for roots to penetrate in soil. In roots, the effective turgor pressure is described by growth pressure, and the maximum growth pressure for some crop species has been reported to be around 1.0 MPa (Gill and Bolt, 1955; Eavis *et al.*, 1969). Misra *et al.* (1986) reported relatively low root growth pressure (between 0.24 to 0.50 MPa) for sunflower, cotton and pea.

However, some recent studies on water stress reported no correlation between growth rate and turgor pressure (Matsuda and Riazi, 1981; Michelena and Boyer, 1982; Van Volkenburgh and Boyer, 1985; Pritchard *et al.*, 1991 and 1993). These results have led some to question the importance of turgor pressure in wall extension (Goering *et al.*, 1984; Boyer, 1985). Passioura (1994) suggested that the effects of changing water status on expansion rate may be mediated not necessarily through turgor, but possibly

through the hydration of the cell wall, which may shrink at low water potential, thereby inactivating enzyme molecules by restricting their freedom of movement.

2.4 Soil Physical Properties and Root Growth

Many factors affect root growth. It is necessary to separate factors that directly affect plant root growth from those which indirectly affect plant growth. Water, oxygen, temperature, and soil strength all directly affect root growth. Soil bulk density, texture, aggregation, aggregate stability, and pore size distribution affect root growth indirectly through their effects on water, aeration, temperature and soil strength (Letey, 1985).

2.4.1 Soil Water and Root Growth

Soil water status is one of the most important soil physical properties affecting root growth and function. All land plants are water-stressed to some extent (Sands and Mulligan, 1990). The roots are almost always surrounded by excessive or inadequate water. Excessive water (flooding, waterlogging) prevents aeration of the soil and inhibits the respiration of roots. This is a stress really created by anaerobiosis and will be discussed in 2.4.2.

The parameters describing the soil moisture environment include gravimetric water content and volumetric water content and soil water potential. Soil water potential describes the force that a plant is required to exert to overcome the forces of adhesion and cohesion that bind the water to the soil. Therefore soil water potential is more directly associated with root growth than soil water content. According to Jury *et al.* (1991), the water potential (Ψ) in an unsaturated rigid soil can be described as:

$$\Psi = \Psi_z + \Psi_\pi + \Psi_a + \Psi_m \qquad (2.8)$$

Here Ψ_z (gravitational potential) is the energy per unit volume of water required to move an infinitesimal amount of pure, free water from the reference elevation to the soil water elevation; Ψ_π (solute or osmotic potential) is the change of energy per unit volume of water when solutes identical in composition to the soil solution at the point of interest in the soil are added to pure, free water at the elevation of the soil; Ψ_a (air pressure potential) is the change in potential energy per unit volume of water when the soil air-pressure is changed from the air pressure of the reference state to the pressure of soil; and Ψ_m (soil matric potential) is the energy per unit volume of water required to transfer an infinitesimal quantity of water from a reference pool of soil water at the elevation of the soil to the point of interest in the soil at reference pressure. In most cases, Ψ_z and Ψ_a are very small and negligible, and Ψ_π is also very small in most soils, and the total water potential is assumed approximately equal to the soil matric potential.

$$\Psi \approx \Psi_m \tag{2.9}$$

Root elongation of most plants has been widely observed to decrease progressively as matric potential decreases from nominal field capacity (–0.01 MPa) to permanent wilting point (–1.5 MPa) (Hillel, 1979; Sharp et al. 1988; Kramer and Boyer, 1995). Kaufmann (1968) found that root growth of loblolly pine (*Pinus taeda*) and scots pine (*Pinus sylvestris*) seedlings decreased by 75% as soil matric potential dropped from –0.01 MPa to –0.6 and –0.7 MPa. Sharp *et al.* (1988) reported that the root elongation rate of maize (*Zea mays* L. Cv WF9 × Mo 17) growing in vermiculite decreased progressively as the water potential decreased from –0.03 to –2.0 MPa. The radicle elongation of *Pinus caribaea* var. *hondurensis* was reported to decrease monotonically with decreasing matric potential, ceasing at –1.68 MPa (Constantini *et al.*, 1996a). Usually root growth commences to decrease at a soil water potential of about - 0.05 MPa and ceases at about - 1.5 MPa (Hamblin, 1985). However, Logsdon *et al.* (1987) reported that the root length of maize was not reduced at a matric potential as low as - 1.09 MPa.

According to the root growth model given by Yau and Sands (1992) (Model 2.4), there is a clear positive relationship between root growth rate and soil matric potential. It is therefore understandable that growth is particularly sensitive to a decrease in soil matric potential (Ψ_m).

In fact, stress-induced adaptive changes in a plant are extremely complicated and are often expressed as a systematic reaction. The most obvious change of water stress is inducing the synthesis of ABA, which causes characteristic reactions in all parts of the plant, especially the inhibition of cell extension. Van Volkenburgh and Cleland (1986) considered this to be the most important factor limiting root elongation.

In many plants, medium to severe water stress induces a decrease of osmotic potential by accumulation of osmotically effective substances in the cell sap and in the cytoplasm. This osmotic adaptation is caused by increased uptake or release of metabolites, e.g. sugars, amino acids and ions. Osmotic adaptation theoretically allows a reduction of cell water potential at constant turgor. Details of the physiological regulation of osmotic adaptation are not fully understood. There is little precise data about at which water potential the osmotic regulation will occur. Greacen and Oh (1972) reported that pea roots could osmo-regulate to maintain turgor over a range of soil water potentials from - 0.28 to - 0.80 MPa. This suggests there might be no significant osmotic regulation when soil matric potential is high.

2.4.2 Soil Aeration and Root Growth

Oxygen is necessary to maintain aerobic root respiration so as to supply energy needed for mineral uptake, synthesis of protoplasm, and maintenance of cell membranes (Kozlowski, 1985). An inadequate air-filled porosity will seriously restrict CO_2 diffusion out of the soil and O_2 input into the soil (Ruark *et al.,* 1982) and the plant growth in this soil environment will be seriously restricted.

Oxygen deficiency typically is more serious than CO_2 excess. Slatyer (1967) considered that, so long as O_2 levels are high enough, excess CO_2 could be tolerated. If O_2 levels are low, CO_2 can become very toxic in impervious soils. In addition, CO_2 concentration may be higher and O_2 concentration lower near the root than in the soil as a whole.

Since bad aeration is a direct result of lack of O_2, it seems reasonable to use O_2 concentration to describe the aeration condition in soil. This idea was supported by the following reports. Leyton (1956) reported that reduction in the supply of O_2 to the roots of Norway spruce and Scots pine caused a marked reduction in growth of roots, and complete exclusion of O_2 stopped growth entirely and, if maintained for more than 24 hours, killed the seedling. However, the critical oxygen concentrations in soil air that impair root growth differ between species (Boggie, 1974).

A high O_2 concentration in the soil atmosphere doesn't necessarily mean a high access of O_2 for roots if the O_2 diffusion rate (ODR) is low. MacDonald *et al.* (1993) found that measurements of ODR gave a better indication of oxygen availability in soil than measurements of oxygen concentration. The same O_2 concentration may have a different diffusion rate in the same soil with different bulk density and soil moisture content. ODR was lowest in soils with high bulk density and high soil moisture content. It is supposed that when the ODR is less than 0.20 $\mu g\ cm^{-2}\ min^{-1}$, root growth of most plants is limited (Lunt *et al.*, 1973), while an ODR of greater than 0.4 $\mu g\ cm^{-2}\ min^{-1}$ is termed adequate (McLaren and Cameron, 1990). ODR is better than oxygen concentration in describing the effect of oxygen deficiency on root growth, but different species still have different sensitiveness to ODR (Nishimoto, 1982).

The disadvantage in using either O_2 concentration or ODR as an indicator of the effect of poor soil aeration on root growth is that this ignores other components in soil air. O_2 is critical to respiration, but high CO_2 concentration or the interaction of both O_2 and CO_2 may cause improper functioning of the root. In most cases, especially in the soils contaminated with industrial waste, the interaction of both O_2 and CO_2 is important to

root growth. Chan *et al.* (1991) studied the root system of a range of subtropical woody plants grown in the industrial area in Hong Kong and indicated that a very high CO_2 concentration in cover soil limited the depth of the root system. Trees with a shallow root system became very susceptible to water stress. The effects of low O_2 concentration in soil were less important than the effects of high CO_2 concentration (Chan *et al.*, 1991).

Practically, the most popular, simple and direct measure of soil aeration is air-filled porosity, ε_a. It simply represents the space in the soil occupied by air, and therefore represents the capacity as a buffer to hold O_2 and exchange O_2 with the atmosphere. High air-filled porosity in coarse soil, low bulk density soil or drying soil indicates a better aeration condition, and lower air-filled porosity in fine textured soil, compacted soil or waterlogged soil indicates a worse aeration condition. Soil air-filled porosity may also have the advantage that it integrates to some extent the effects of all gases in the soil atmosphere.

There is disagreement about the exact value of the critical level of ε_a. It has been widely accepted in past research and literature that the root growth of most plants will be severely restricted when soil air-filled porosity reaches 0.10 cm^3 cm^{-3} or lower (Baver and Farnsworth, 1940; Sands and Bowen, 1978, Theodorou *et al.*, 1991; Xu *et al.*, 1991). Patt *et al.* (1966) found a critical limit of 9 -10 per cent air space existed at field capacity at the 25-75 cm depth for fine root penetration of citrus trees. Soil air-filled porosity smaller than 0.10 cm^3 cm^{-3} was found to significantly retard root growth of radiata pine (Theodorou *et al.*, 1991). Again, air-filled porosity less than 0.12 cm^3 cm^{-3} limited root growth of yellow-poplar (*Liriodendron tulipifera* L.) and sweet gum (*Liquidambar styraciflua* L.) seedlings grown in compacted soil (Simmons and Pope, 1988).

In addition, the low air-filled porosity caused by soil compaction is always associated with an increase of soil strength. Increased soil strength might contribute heavily to the reduction of root growth observed under this situation. Often the literature does not

consider the interacting effect of reduced air and increased strength on root growth in compacted soils. The physiological basis for the compound effect of reduced air and increased strength on root growth is still poorly understood.

The concept of a critical level of air-filled porosity for root growth assumes that growth is satisfactory above this level and suddenly unsatisfactory below it. Penfold (1998) tested whether this was so in controlled environment experiments in the laboratory. He investigated the quantitative relationship between the root growth rate of radiata pine and soil air-filled porosity using repacked soil under controlled soil water and soil strength. The results showed that root growth at low air-filled porosities was insignificant at air-filled porosities < 0.06 cm^3 cm^{-3} after which it increased asymptotically and gradually to a maximum around 0.16 cm^3 cm^{-3}. This suggests that the concept of a critical level of soil aeration is somewhat simplistic. However, Penfold (1998) clearly showed that root growth of radiata pine seedlings was unaffected at values of air-filled porosity ≥ 0.16 cm^3 cm^{-3} and this has been used in the experiments reported in this thesis to define non-limiting aeration conditions. It also demonstrates that the unquestioned acceptance of 0.10 cm^3 cm^{-3} as a universal critical limit irrespective of species and soil pore size distribution could be misleading. In his study he showed that reductions in root growth resulting from reduced soil air were gradual rather than sudden and that reductions in root growth still occured at air-filled porosities ≥ 0.10 cm^3 cm^{-3}.

2.4.3 Soil Strength and Root Growth

Soil supplies water, nutrients, aeration and anchorage for root growth. Soil is so important and essential for root growth that we don't even think of its detrimental effect on root elongation. Gingrich and Russell (1956) compared a series of soil samples and mannitol solutions of corresponding stresses as to their effect on water absorption and plant growth. Their results showed that the roots grew better in osmotic solutions than in soil samples having the same water stress, and this effect was reported by several investigators (Ayers *et al.* 1943, Eaton, 1941). At that time, this was a quite confusing

result because there was no reason to believe roots could detect water stress derived either from matric potential or osmotic potential as water stress itself acts as a physical process in the first place. At present, explanation of this result is quite simple - this difference is obviously partially, if not totally, contributed by the existence of soil mechanical impedance to root penetration in the soil sample.

Although soil strength is a factor directly influencing root growth, its importance was not recognised and emphasised until an acceptable method to measure it was available. Soil strength increases in drying soils but the effect of soil strength in reducing root growth in drying soils often has been ignored. Often in the literature the effect of drying soil on root growth has been attributed to water stress (a reduction in soil water potential) without consideration of the accompanying increase in soil strength. It is still difficult to separate the contributions from soil strength and water stress on root growth in soils at low water content (Costantini *et al.*, 1996a). Therefore the quantitative determination of the influence of soil strength on root growth is still a challenge for any further soil physical and root physiological studies.

When a root tip growing in a structured soil encounters the surface of an aggregate, three possible pathways may be followed (Whiteley and Dexter 1984). Firstly, the root may bend to avoid the aggregate and penetrate through the existing pores without deforming the soil matrix; secondly, the root may penetrate the aggregate and grow through it; and finally the root may displace the aggregate from its path. In most soils, roots grow partly through existing pores and partly by moving aside soil particles (overcoming mechanical impedance). The actual path way followed will be a result of both the size and the strength of the aggregate and the maximum growth pressure that the root can exert (Gregory, 1994). The ability of the plant root to find space in which to grow, or the mechanical impedance root growth has to overcome is often an important factor limiting plant growth.

Qualitative information on root penetration resistance can be obtained by visual observations of the resultant modification in root form. However the most meaningful

and practical way is to establish the quantitative relationship between root growth and certain soil factors which can be readily measured. Soil bulk density had been used as this factor at the beginning (Schuurman, 1965) because it is the most immediate and easily measured factor to reflect soil restraint to the root. The increase of bulk density should increase mechanical restraint and therefore have a negative influence on root extension. The disadvantage is that increasing or decreasing of bulk density is associated not only with the mechanical impedance, but both soil aeration and available water will also change, and the observed result is far from a quantitative description of the effect from mechanical impedance alone. Also, the relationship between soil strength and bulk density differs between soil types. Bulk density is site-specific. Soil strength is generic in that a given value should have the same effect on root growth irrespective of soil bulk density.

2.4.3.1 Soil Mechanical Impedance and Soil Strength

In order to elongate in soil, a root has to penetrate through the soil matrix. Soil offers a certain resistance to root penetration: the resistance is called soil mechanical impedance to root elongation (P_s). Because soil mechanical impedance cannot be directly measured (Russell, 1977), penetrometer resistance (soil strength) has been widely employed as a fast and effective way of measuring the resistance the soil offers to potential root growth (Warkotsch, 1994). In practice, soil strength, which is measured by pushing a cone-penetrometer into the soil matrix at a constant speed, is used to qualitatively describe the mechanical impedance (Greacen *et al.*, 1968; Sands *et al.*, 1979; Bengough, 1991; Bengough and Mullins, 1991; Misra and Li, 1996).

The relationship between mechanical impedance and soil strength is very complicated and is only partially understood. The value of soil strength of the same soil sample depends on both the cone angle of probe and the diameter of the cone probe base. When a soil strength value is given, it is important to describe the specifications of the penetrometer used in determining this soil strength. Misra and Li (1996) found the

penetrometer resistance is independent of probe diameter when the diameter of the probe is over 2 mm (probe diameter indicates the cone base diameter) and indicated probes of larger diameter commonly used in the field are likely to provide as reliable estimates of penetrometer resistance as those probes of small diameters used in the laboratory. Bengough and Mullins (1991) indicated soil strength measured by a 5^0 semiangle, 1mm diameter probe was approximately the same as the resistance to root penetration (mechanical impedance) after subtracting the frictional component of resistance. However, a 5^0 semiangle and 1 mm diameter probe is not practical in field soil strength measurement. The most widely used penetrometers in the field are equipped with a 30^0 semiangle with a probe diameter larger than 2mm.

It is generally believed that the soil strength value is larger than the mechanical impedance. The direct evidence is that the measured maximum pressure roots can generate is smaller than penetrometer soil strengths at which roots are known to elongate. Pfeffer (1893) reported the first detailed study of the pressures which roots can exert. He found that roots could exert longitudinal pressures of about 1.0 MPa and radial pressures of rather more than half this magnitude. Then a number of studies by other investigators (Gill and Bolt, 1955; Barley, 1962; Stolzy and Barley, 1968; Taylor and Ratliff, 1969b) indicated that roots of a number of species could exert longitudinal pressures between 0.7 and 1.5 MPa with values of about 1.0 MPa being common (Dexter, 1987). The penetrometer soil strength roots can successfully penetrate is higher than this pressure. The roots of radiata pine can grow in soil up to 3 MPa (Sands *et al.*, 1979).

Efforts to relate the penetrometer soil strength to root penetration resistance have been made by some researchers (Greacen *et al.*, 1968; Bengough and Mullins, 1991). One potential method to estimate the pressure exerted by roots at a given value of soil strength is to convert soil strength from a 5^0 semiangle, 1mm diameter probe to normal stress, N, by using the equation given by Greacen *et al.* (1968)

$$N = Q/(1+\cot\alpha \tan\phi) \qquad (2.10)$$

where α is the probe semiangle, Q is the point resistance and ϕ is the angle of soil-metal friction.

This method is not widely used because it is very difficult to decide the soil friction since it depends on soil moisture, soil texture and soil density.

Therefore soil mechanical impedance to root penetration is still a very conceptual term, precise determination of soil mechanical impedance requires further work.

2.4.3.2 Quantitative relation between soil strength and root growth

According to the root growth model given by Yau and Sands (1992), the difference between root growth in soil from root growth in solution is the mechanical impedance in soil. It was reported that application of external pressure of around 0.20 MPa to sunflower leaves actually stopped their expansion (Boyer, 1968). To determine the minimum pressure to appreciably reduce root elongation, quite a few investigations have been carried out (Gill and Miller, 1956; Barley, 1962, 1963; Abdalla *et al.*, 1969; Russell and Goss, 1974 and Goss, 1977). The investigators grew roots in known external pressure that was transmitted through membranes or diaphragms, all other conditions being maintained uniform and favourable. They showed a reduction of root extension caused by external pressures in the range of 0.025 - 0.05 MPa (Russell, 1977). Root elongation rate was reported to reduce about 50 - 60% of that of unimpeded controls by an applied external pressure of between 0.26 and 0.47 MPa (Eavis, 1967, Bengough and Mullins, 1991). This clearly shows that roots are very sensitive to the external pressure. In real soils, even the optimal soil condition may have soil mechanical impedance far higher than this pressure. This suggests that root growth may be impaired in low strength as well as high strength soils. This is not commonly recognised.

Sands *et al.* (1979) showed that root growth of radiata pine growing in a well-aerated sandy soil was restricted above a soil strength around 3.0 MPa. However this value is arbitrary and it would be a mistake to interpret this as a step function where growth at soil strengths below 3.0 MPa is considered to be satisfactory while root growth at soil strengths above 3.0 MPa is considered to be suddenly seriously restricted. Rather, evidence suggests that the growth rate and abundance of roots decreases exponentially with increase in soil strength, which means that the greatest rate of decrease in root growth or abundance is actually in the low soil strength range rather than the high soil strength range (Greacen and Sands, 1980) (Figure 2.1). This reinforces the fact that root growth can be affected by soil strength in soils that are of low soil strength and not normally considered to be compacted.

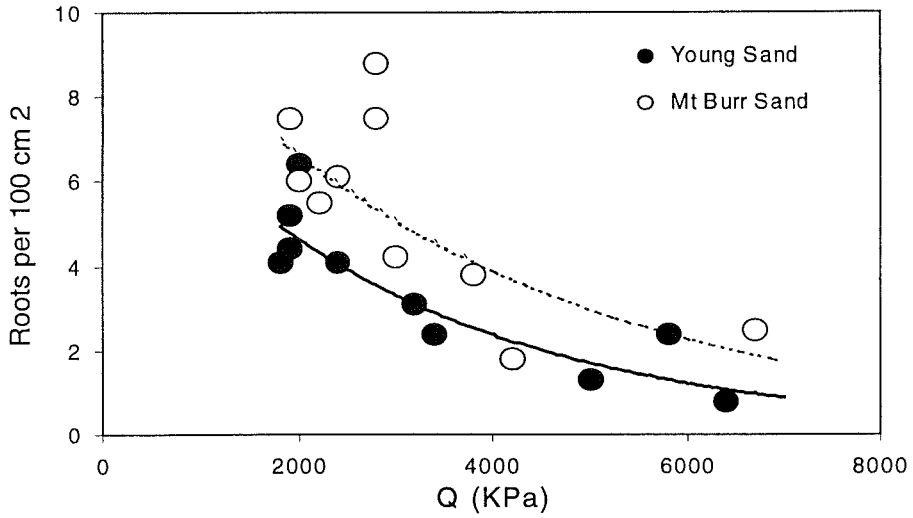


Figure 2.1. The relationship between frequency of roots (number per 100 cm^2) of radiata pine and soil strength Q (kPa) of Mt Burr sand and Young sand (Redrawn from Greacen and Sands, 1980, p 178)

However, it cannot be concluded from Figure 2.1 that soil strength is the sole factor determining root growth since there is no explanation about soil aeration, water distribution and nutrition in this experiment.

To fully understand the response of root growth (elongation) to soil strength, it requires all the associated factors to be constant or clearly non-limiting. High soil strength can be achieved by increasing soil bulk density or decreasing soil water content. Increasing soil bulk density will reduce soil air filled porosity and affect the soil aeration, and decreasing soil water directly creates water stress.

2.4.4 Root Growth — An Integrated Response to Soil Matric Potential, Soil Strength and Soil Air-filled Porosity

Root growth is determined by its internal physiology and its external soil environment. Soil aeration supplies O_2 to support the oxidation-energy-producing process. Soil strength helps to anchor the root system but also exists as an inverse force to restrain root elongation. Soil water is required by roots for normal function and a shortage of soil water reduces root growth from water stress but also from increased soil strength.

Soil air-filled porosity is related to soil matric potential and soil strength. A lower air-filled porosity is associated with a high matric potential (water logging) and/or high soil strength (serious compaction). Phene and Beale (1976) reported that a critical soil matric potential higher than -0.008 MPa would result in oxygen deficiency in sandy loam to retard plant growth. Eavis (1972) considered the simultaneous effects of soil water, soil strength and soil aeration in restricting pea seedling root growth and suggested that the effect from air-filled porosity was only effective when soil matric potential was higher than a certain water potential. More recent studies indicated that an air-filled porosity of 0.16 cm^3 cm^{-3} is ideal for root growth of radiata pine in repacked soil (Penfold, 1998). All the above results suggest that the effect of air-filled porosity can be isolated from soil matric potential and soil strength and it is possible to discuss the interactive effect of both soil matric potential and soil strength providing a sufficient air-filled porosity is given.

Usually when the soil water content decreases, there is an increase in soil strength and the root elongation rate decreases (Greacen and Sands, 1980). Whether this decrease is

due to the increase in soil strength or lowered soil water potential or to combination of both is not clear. One opinion is that there is no or very limited effect of soil moisture on root elongation and the reduced root growth in decreased soil water content is mostly from the increased soil strength (Barley *et al.*, 1965; Taylor and Ratliff, 1969a; Greacen and Oh, 1972). An opposite opinion is that reduced root elongation is largely related to moisture stress (Mirreh and Ketcheson, 1972; Bar-Yosef and Lambert, 1981). More recent studies indicate that reduced root growth is a combined effect of both decreased soil water and increased soil strength (Gerard *et al.*, 1982; Davis, 1984).

Davis (1984) studied the relative importance of soil moisture potential and soil strength on the root elongation of radiata pine in a sandy loam soil. The results showed that the root elongation rate decreased with decrease of soil matric potential at both 1.3 MPa and 2.0 MPa soil strength, with a significant different initial elongation rate, which was attributed to a difference in soil strength. Davis (1984) also showed that the effect from soil matric potential was very small at extremely high soil strength (4.5 MPa) and the root elongation rate was almost constant at 1 mm day^{-1} over the soil matric potential range (-0.01 MPa to -1.5 MPa). This suggests that water potential may have a greater effect in soils of low than high soil strength.

Root growth reduction either in compacted or drying soil is a combined result of soil air, soil water and soil strength. However the relative contribution of these factors will vary with soil type and condition. For example, Sands and Bowen (1978) concluded that the reduced root penetration of radiata pine in a compacted sandy soil was probably due to the greater resistance offered by soils of higher strength to root penetration rather than to reduced aeration. A further understanding of this interaction will rely on successful establishment of a root growth model including these physical properties.

2.5 Soil Compaction and Radiata Pine Growth — New Zealand Trial

Reports on adverse effects of soil compaction on forest productivity in New Zealand are not as numerous as in some other countries. This may partially be because the improved genetic performance of trees and advanced silvicultural practices such as weed control, fertilisation, pruning and thinning have masked the effects of compaction (McMahon, 1994).

However, the soil compaction problem does exist. As early as in 1975, there was a report on the effect of heavy machinery harvesting on the survival and early growth of second-rotation *Pinus radiata* seedlings (Berg, 1975). Since then quite a few reports about the effect of harvesting have been documented (Murphy, 1983; Firth, *et al.*, 1984; Mason *et al.*, 1988; Firth and Murphy, 1989; Hall, 1993; McMahon and Evanson, 1994; Smith, 1994; Murphy *et al.*, 1997).

Simcock *et al.* (1995) conducted a study on compaction on an immature Orthic Pumice soil in Kinleith forest, Tokoroa and indicated that seedling survival and height was greater on uncompacted and ameliorated treatments than on compacted treatments. However the Riverhead trial reported compaction had no effect on seedling height or root collar diameter of radiata pine in a clay loam soil (Simcock *et al.*, 1997). Depression of tree height was strongly correlated with increased topsoil bulk density. The number of roots was inversely related to soil strength, with eight times more roots in the 0.2 to 0.60 m zone in ripped treatments than unripped treatments. The most recent report made by Murphy *et al.* (1997) described the effect of soil disturbance related to logging on the productivity of *Pinus radiata* D. Don growing on a clay loam soil in Maramarua Forest, New Zealand. The results showed that tree volumes at age 11 years were reduced by about 20% where litter had been removed by machine; about 55% where the topsoil had been removed and subsoil compacted with 2 passes of a

loader; and about 65% where the topsoil had been removed and the subsoil compacted with 8 passes of a loader.

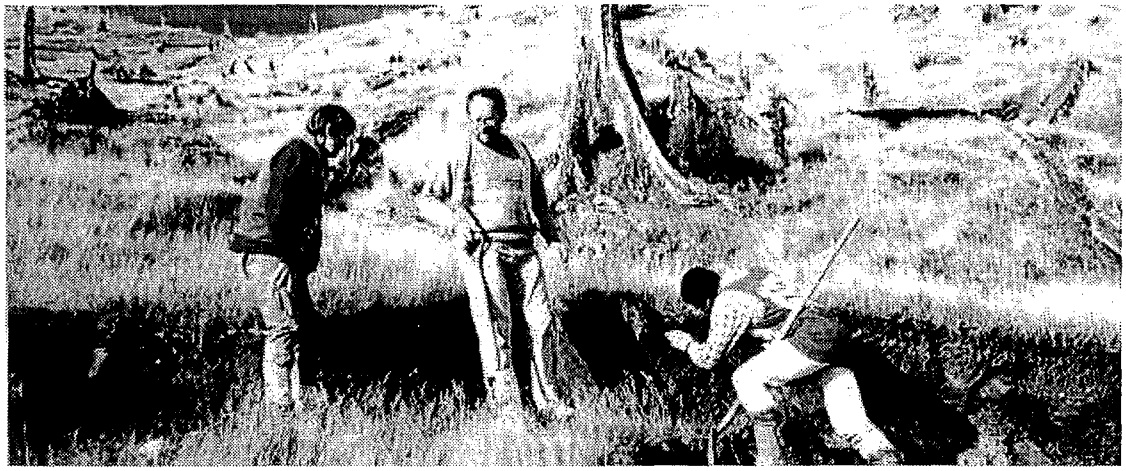
In New Zealand, compacted soil can only slowly recover by natural influences because few forest soils are subject to frost action or shrinking and swelling (dry-wet) cycles (Squire *et al.* 1991). Natural alleviation is particularly slow in subsoil due to the low activity of roots and soil organisms (Gameda *et al.*, 1994) and many may not recover between harvests. The effects of soil compaction from successive harvests may, therefore, be cumulative, especially given the short rotation lengths in New Zealand. Therefore site productivity for further rotations may be progressively decreased. Mason *et al.* (1988) reported that ripping/bedding caused a significant improvement in height and diameter growth between 2 and 7 yr. old of radiata pine. Simcock *et al.* (1995) reported the survival rate of seedlings to 2 years-old trees was 30 % higher on the control or ripped treatment compared to the compacted site.

In the South Island of New Zealand, emphasis should be given to climate. During drought or in a dry climate like in Canterbury, soil compaction will increase soil strength and worsen the water shortage problem. In a wet climate like the West Coast, compacted soil will worsen the water drainage problem, and the worse aeration problem will limit tree growth.

In New Zealand, harvesting of native forests is limited, and soil compaction problems related with harvesting are almost always referred to plantations. Plantations can be either good or bad for soil and site productivity. Sustainable forestry centres on the wise management of soil (Powers and Morrison, 1996). Careful forest management can maintain or improve soil physical properties. However, inappropriate use of machinery in site preparation and harvesting can cause soil compaction and erosion and reduce site productivity.

CHAPTER 3

SOIL COLLECTION AND CHARACTERISTICS



Prof Roger Sands (middle, New Zealand School of Forestry), Dr Elaine Birk (left, Rayonier NZ Ltd) and Mr Ian Bell (right, Rayonier NZ Ltd) collecting soil samples in Gisborne

3.1 Abstract

Four soil types (pumice, argillite, ash and loess) of different textures were collected from the plantation property of Rayonier New Zealand Ltd. Soil texture, soil particle density, soil organic matter content, soil pH and soil nutrients in each soil texture were measured.

The textures of pumice, argillite, ash and loess were loamy sand, loam, sandy clay loam and silty clay respectively. Among the four soil textures, pumice had a relatively low particle density of 2.44 g cm^{-3} and the lowest organic matter content of 2.06%. The low particle density in pumice was mainly determined by the low mineral particle density.

Ash had the lowest particle density of 2.41 g cm^{-3} and the highest organic matter content of 7.97%. Argillite had a particle density of 2.55 g cm^{-3} with a medium organic matter content of 5.88 %. Loess had a particle density of 2.53 g cm^{-3} and a relatively lower organic matter content of 2.14%.

The pH of the four soils was adequate for growing radiata pine. Both ash and argillite had balanced nutrients that were adequate for radiata pine growth. In pumice soil, the Bray Mg value was critically low, and Mg fertiliser was required. In loess, Bray K values were extremely low, and K fertiliser was required to maintain K nutrition.

The four soil textures represent different soil particle size distributions, have different particle densities and organic matter contents. Changing bulk density and water content in the four soil textures can achieve the range of combinations of soil matric potential, soil strength and soil air-filled porosity necessary to evaluate them singly and in combination in experiments to be described later.

Key Words: Soil particle size distribution; soil particle density; soil organic matter and organic carbon; soil pH and nutrients

3.2 Introduction

Both soil water potential and soil strength affect root growth in soil. However, it is not possible to directly vary one while holding the other constant. As a soil dries its soil strength will increase. Using soils of different texture will assist to establish a complete combination of values of soil water potential, soil strength and soil air-filled porosity to analyse the interaction of these physical properties by a modelling approach. In order to examine the effect on root growth of changing matric potential at constant soil strength and conversely the effect of changing soil strength at constant water potential, it is necessary to measure root growth over a large range of soil textures and bulk densities.

By doing so a data set can be assembled where large ranges of matric potential can be compared at small ranges in soil strength and vice versa. It is possible then to isolate the effects of soil matric potential from soil strength.

Soil particle densities were measured in order to calculate soil porosity. Particle size distributions were determined after organic matter was removed. However, soil organic matter can have an important effect on pore size distribution, water retention and associated physical properties. Organic matter therefore was also measured in order to evaluate its contribution to pore size distribution in the four soils. Soil pH and soil nutrients were measured to determine whether they were adequate for root growth.

3.3 Materials and Methods

3.3.1 Collection of Soils and Soil Profile Description

Four soil types were collected from the plantation properties of Rayonier New Zealand Ltd. The four soil types were pumice and ash from a recently harvested site on 402 Waituhi Forest, Taupo, argillite from a nearly mature radiata pine plantation in Cpt 96, Gisborne, and loess from the Longwood Forest in Ohai, South Island. All these soil samples were collected from the top 20-cm of soil after the surface litter and debris were removed.

3.3.1.1 Pumice

Pumice soil comes from rhyolitic tephra, with at least the top 50 cm of the profile developed in tephras, which are between 660 and 3500 years old (Molloy, 1993). It is the predominant soil of the volcanic plateau of the central North Island of New Zealand, and it is also scattered through the Bay of Plenty and Hawke's Bay. In this area the soils are derived almost entirely from pumice, the distinctive soft, greyish-white, frothy, volcanic rock which mantles most of the land.

The thickness and darkness of the A horizon is closely related to the vegetative cover, e.g. deep and black under fern, shallow and grey under manuka scrub, and brown under podocarp/hardwood forest; the B horizon becomes more reddish-brown as the pumice soils become more leached (Molloy, 1993).

Because the soil parent materials were deficient in a number of trace elements important for animal health, this led government and private industry to establish large areas of the pumice lands in exotic forest (principally *Pinus radiata* D. Don), particularly during the depression years. Today, exotic forests cover 400 000 ha of the Rotorua - Taupo basin pumice lands, an important forest resource making up 40 percent of the entire exotic forest estate in New Zealand (Molloy, 1993).

3.3.1.2 Ash

Ash soil comes from air-fall tephras (both rhyolitic and andesitic), generally between 3500 and 50 000 years old and also from alluvium or loess containing a high proportion of this tephric material (Molloy, 1993). A-horizons are moderately deep (15 - 25 cm) and black to brown in colour. B-horizons are quite deep (20 - 60 cm) and commonly yellow brown in colour, but some are red-brown in higher rainfall areas (Molloy, 1993).

3.3.1.3 Argillite

Argillite soil indicates the recent alluvial soils developed from the highly erodible tertiary mudstone and shattered argillite in the Gisborne-East Cape hill country. The recent alluvial soils occur on the flooding plain and lower terraces of rivers. They are formed from predominantly sandy and silty material (alluvium) eroded from the rocks of the catchment, which are sorted and deposited in layers during flood events (Molloy, 1993).

Although these recent alluvial soils vary widely in the nature of the parent rock of the alluvium, their youthfulness is their common characteristic. Generally, insufficient time has passed since the alluvium was deposited for a well-structured B-horizon to form. Development is limited to an A-horizon (which is thicker in soils which are flooded less frequently) (Molloy, 1993).

3.3.1.4 Loess

This is an important lowland brown earth of the Southland Plains. They have developed in deep loess over weathered gravel. The subsoil is a uniform yellowish brown in colour with the B-horizon passing from silt loam to silty clay in texture (Molloy, 1993).

3.3.2 Preparation of Soil Samples

All the soil samples collected from the field were passed through a 2 mm sieve and all particles and gravel with diameter larger than 2 mm were discarded. Sieved samples were kept in plastic bins with lids to prevent the soils from drying out and losing their aggregate structure. The sample bins were opened for 10 – 15 minutes every week to inhibit any toxicity that might have been caused by anaerobes (Misra, 1997, personal communication).

3.3.3 Mechanical Analysis

The hydrometer method described by McIntyre and Loveday (1974) was used for mechanical analysis. Some modifications were made and the experimental procedures are described as following:

3.3.3.1 Pre-treatment and Removal of Soil Organic Matter

1. About 40 g of the air-dry soil was weighed and placed into a 1000 ml flask. About 500 ml distilled water was added to the flask which was shaken to get the soil in suspension.

2. 100 volume 30% hydrogen peroxide was added to the flask until frothing had ceased and most of the organic matter had been oxidised. The required volume of hydrogen peroxide ranged between 20 – 50 ml depending on the organic matter content of the soil. The suspension was heated to about 90 ^{0}C, and extra hydrogen peroxide was added if frothing reoccurred. The suspension was heated for a further 45 minutes following the last addition of hydrogen peroxide to ensure that any excess hydrogen peroxide was removed. The suspension was then allowed to cool to the laboratory temperature before further measurement.

3. Another sample of the same soil (about 10 g) was weighed, dried for 48 hours at 105^{0}C, cooled, and re-weighed for determination of gravimetric soil water content (θ_m: g g^{-1}).

3.3.3.2 Measurement Procedures

1. 100 ml of 50 g/l Calgon* solution was added to the pre-treated soil suspension and the flask was tightly sealed with a plastic stopper and shaken overnight with a shaker followed by 24 hours on an end-over-end shaker.

2. The suspension was transferred to a 1000 ml measuring cylinder. The flask was washed several times with distilled water to make sure all the soil particles in the flask were transferred to the cylinder. Distilled water was added to the cylinder to a little less than one litre.

* Sodium hexametaphosphate. Albright & Wilson Australia Ltd

3. The suspension was equilibrated at 20^0C room temperature and distilled water added to the cylinder to exactly one litre.

4. The contents were mixed thoroughly using a plunger. The sediment was dislodged with strong upward strokes of the plunger near the bottom and by spinning the plunger while the disk was just above the sediment. The stirring was finished with two or three slow, smooth strokes. The time of completion of stirring was recorded and a drop of amyl alcohol was added if the surface of the suspension was covered with foam.

5. The hydrometer* was carefully lowered into the suspension and a reading was taken after 12 minutes ($\boldsymbol{R}_{12\min}$, g / l).

6. The hydrometer was carefully removed after the 12 minutes reading, rinsed, and wiped dry. The suspension was incubated at 20 ^{0}C.

7. A further hydrometer reading was taken at 20 hours (R_{20h}).

8. There were at least three replicates for each soil.

3.3.3.3 Calculations

$$\text{Sand } \% = \left[1 - \frac{R_{12\,\min} - R_{ca\,\lg on}}{Wt_{soil} \times (1-\theta m) \times (1-OM)}\right] \times 100\% \quad (3.1)$$

$$\text{Clay } \% = \left[\frac{R_{20h} - R_{ca\,\lg on}}{Wt_{soil} \times (1-\theta m) \times (1-OM)}\right] \times 100\% \quad (3.2)$$

$$\text{Silt } \% = 100 - (\text{sand}\% + \text{clay}\%) \quad (3.3)$$

* Gallenhamp Soil Hydrometer 0-60 SH 165

In Equation 3.1 and 3.2, R_{calgon} is the reading for the blank (no soil) solution, Wt_{soil} is the air-dry mass of sampled soil (g), θ_m is the gravimetric water content (g g^{-1}) and OM (g g^{-1}) is the organic matter content determined by the dichromate method (see 3.3.5 Organic Matter Analysis).

3.3.4 Particle Density Analysis

Soil particle density (ρ_s) was measured based on the principles described by McIntyre and Loveday (1974), but in this experiment a 50 ml volumetric flask was used to replace the normal pycnometer and the measurement procedures are described as follows:

3.3.4.1 Measurement Procedures

A 50 ml volumetric flask was weighed (W_{flask}) (± 0.001 g), and 25 g (± 0.001 g) of air-dry soil was placed in the flask. The flask was filled with distilled water to one-half to three quarters full, washing any soil adhering to the inside of the neck. The air in the soil pores was removed by boiling the liquid in the flask for 30 minutes. The flask and contents were allowed to cool to room temperature, and the volume was made up to exactly 50 ml with distilled water. The final weight of the flask with water and soil (W_{total}) was measured. The temperature of the solution was measured and the corresponding density of water (ρl) was read from tables given by Loveday (1974). There were 3 replicates for each soil.

3.3.4.2 Calculation

The particle density of soil can be calculated by the following formula:

$$\rho_s = W_{soil} / V_{soil}$$
$$= W_{soil} / (50 - W_{water} / \rho l) \qquad (3.4)$$

where ρ_s is the soil particle density, W_{soil} is the oven-dry mass of soil [$W_{soil} = 25 \times (1-\theta_m)$], W_{water} is the mass of water ($W_{water} = W_{total} - W_{flask} - W_{soil}$), ρl is the density of water at the temperature of measurement.

3.3.5 Organic Matter Analysis - Dichromate Method

Soil organic carbon can be almost completely oxidised by gently boiling for 2 hours with an acid dichromate solution. The excess dichromate can be determined by titration with ferrous sulphate using the Walkley-Black procedure (Nelson and Sommers, 1982; Tiessen and Moir, 1993).

3.3.5.1 Principles

The reaction of organic carbon with potassium dichromate can be represented as:

$$2K_2Cr_2O_7 + 3\ C_{organic} + 8H_2SO_4 = 3CO_2 + 2Cr_2(SO_4)_3 + 2K_2SO_4 + 8H_2O \qquad (3.5)$$

The amount of potassium dichromate used in the experiment is determined by titration against ferrous sulphate. The reaction is:

$$K_2Cr_2O_7 + 6\ FeSO_4 + 7H_2SO_4 = Cr_2(SO_4)_3 + K_2SO_4 + 3Fe_2(SO4)_3 + 7H_2O \qquad (3.6)$$

The potassium dichromate solution might oxidise on standing and a dichromate solution without soil was used as control in each batch of soil determinations.

3.3.5.2 Procedures

All pre-sieved soils were air-dried first and the water content of each soil was determined. About 40 g of each soil was ground in a mortar and pestle and mixed well.

The precise soil mass required in the digestion flask differed between soils. The higher the organic matter was, the less quantity that was used. A pre-trial was carried out to decide the precise quantity of soil required based on the consumption of ferrous sulphate. In this experiment, the quantity of soil (Wt_{soil}, ± 0.001 g) used for digestion was 0.4 g in ash, 0.7 g in argillite and loess, and 1 g in pumice.

These pre-determined weights of soil were placed into each of three digestion flasks and 40 ml digestion mixture (0.066 *M* potassium dichromate and 9 *M* sulfuric acid solution) was added. A fourth control digest flask contained digestion mixture alone. The flasks were placed on a hot plate and fitted with condensers. The solutions were boiled at 130 - 135 ^{0}C for 2 hours. The flasks were removed, cooled and about 100 ml of distilled water and 10 ml 85% H_3PO_4 and 2 ml of the indicator* were added in each flask and the solution was titrated against 0.4 *M* ferrous sulphate solution. The solutions were dirty brown initially, and then became purple just before the end point. At this stage the ferrous sulphate was added drop by drop until the colour changed to bright green. The volume of ferrous sulphate used in sample (V_{soil}, ml) and control ($V_{control}$, ml) were recorded to calculate the organic carbon.

3.3.5.3 Calculation

$$C_{organic}\ (mg\ g^{-1}\ _{oven\text{-}dry\ soil}) = 1.2 \times (V_{control} - V_{soil}) / Wt_{soil} \qquad (3.7)$$

The average organic carbon content of the soil organic matter is conventionally assumed to be 58%, so

$$OM = C_{organic} / 0.58 \qquad (3.8)$$

* Barium diphenylamine sulfonate

3.3.6 Soil pH and Nutrient Analysis

Measurement of soil pH was based on the method described by Tucker and Bealty (1974) and some changes were made and described in the procedures:

3.3.6.1 Procedures

20 g of air-dry soil (< 2mm) was added to a 150 ml suspension bottle with 100 ml distilled water. After shaking for 1 hour, the suspension was allowed to settle for 0.5 hour. A JENWAY 3100 Microprocessor pH meter* was standardised with buffer solutions of pH 7.00 and pH 4.00. The electrode was inserted into the soil suspension bottle, keeping the electrode as near to the suspension as possible. The pH was read directly from the meter to the nearest 0.01 of a unit. The electrode was washed with distilled water and the excess water dried off by blotting with filter paper. All measurements were at room temperature (16 -17.6^{0}C), and there were three replicates.

Determination of soil nutrients was carried out by the Forest Nutrition Laboratory, New Zealand Forest Research Ltd. Total nitrogen, Bray phosphorus, Bray potassium, Bray calcium and magnesium were measured (Appendix 1).

3.4 Results

3.4.1 Mechanical Analysis

The percentages of sand, silt and clay in the four sampled soils are listed in Table 3.1.

According to the International Soil Science Society (ISSS) Classification Standard, the pumice, argillite, ash and loess have textures of loamy sand, loam, sandy clay loam and silty clay, respectively.

* Jenway 3100 Microprocessor pH Meter. Jenway Ltd., Essex, UK

Table 3.1. Particle size distribution and classification of four soil textures

Particle Size	Pumice	Argillite	Ash	Loess
% Sand (2.0 - 0.02 mm)	83.81	50.48	56.89	28.56
% Silt (0.02 -0.002 mm)	8.08	30.84	22.70	31.04
% Clay (<0.002 mm)	8.11	22.67	20.40	40.40
Texture Classification	loamy sand	loam	sandy clay loam	silty clay

3.4.2 Particle Densities

The particle densities of the four soil textures are given in Table 3.2. In spite of its coarse texture, pumice had a relatively low particle density of 2.44 g cm^{-3}. Ash had the lowest particle density of 2.41 g cm^{-3}. Both argillite and loess had middle particle densities of 2.55 and 2.53 g cm^{-3}, respectively (McLaren and Cameron, 1996).

Table 3.2. Particle densities of four soil textures

Soil Type	Pumice	Argillite	Ash	Loess
Particle Density (g cm^{-3}) (± STD)	2.44 ± 0.014	2.55 ± 0.003	2.41 ± 0.008	2.53 ± 0.014

3.4.3 Total Carbon and Organic Matter Content

The organic matter contents were significantly different between the four soil textures (Table 3.3). For each soil, at least 3 replicates were measured and the data listed in the Table 3.3 were the average of the replicates.

Table 3.3. Soil total carbon and organic matter content (± STD)

Soil Type	Pumice	Argillite	Ash	Loess
Total C (g /100g)	1.19 ± 0.067	3.42 ± 0.095	4.61 ± 0.173	2.15 ± 0.08
OM (g/100g)	2.06 ± 0.12	5.88 ± 0.16	7.95 ± 0.29	3.71± 0.14

3.4.4 Soil pH and Nutrients

The pH and the N, P, K, Ca and Mg concentrations in the four sampled soils are listed in Table 3.4.

Table 3.4. pH and nutrient analysis in four sampled soils

Nutrients	Pumice	Argillite	Ash	Loess
Total N (g/100g)	0.104	0.289	0.508	0.084
Bray P (mg/kg)*	12.17	6.99	21.17	1.74
Bray K (cmol/kg)	0.11	0.54	0.39	0.09
Bray Ca (cmol/kg)	0.95	3.94	7.59	0.84
Bray Mg (cmol/kg)	0.08	1.6	1.06	1.59
pH	5.32	4.95	4.83	5.22

* Bray- 2 Test result was chosen. Results for three Bray-P tests are listed in Appendix 1 .

3.5 Discussion

3.5.1 Soils of Contrasting Textures

The primary objective in this chapter was to establish a range of soil textures and this objective has been met. The textures ranged from loamy sand (pumice) to silty clay (loess). The corresponding water, air and strength relationships in these soils will be given in Chapter 4.

The particle density of the mineral phase of most soils approaches that of quartz (2.65 g cm^{-3}) (Miller and Donahue, 1990), but pumice had a low particle density (2.44 g cm^{-3}). The pumice had the lowest organic matter content (2.06%) of all the soils and so the low particle density of the pumice is caused by a lower than normal particle density of the mineral phase. By contrast, the low particle density in the ash (2.41 g cm^{-3}) was caused by its high organic matter content (7.95%). The argillite (2.55 g cm^{-3}) and the loess (2.53 g cm^{-3}) had similar particle densities that were higher than that of pumice and ash. The argillite had a coarser texture (more sand) than the loess (more clay) but the higher organic matter content in the argillite (5.88%) meant that their particle densities were similar (Table 3.3). The soil particle densities were measured in order to determine soil porosities at a given soil bulk density (Chapter 4). Soils with low particle densities will have low bulk densities for a given porosity.

Soil organic matter content influences many soil properties. Higher soil organic matter content will tend to increase the infiltration rate and retention of water in soil. This may increase the water content at field capacity and reduce the air-filled porosity. Higher organic matter will change the degree of aggregation and overall structure and reduce the soil strength by decreasing soil bulk density. Organic matter can increase soil plasticity and its resistance to compaction (Sands *et al.*, 1979). Sands *et al.* (1979) reported that soil strength increased with depth partially because of the increased soil bulk density caused by decreased soil organic matter.

3.5.2 Soil Texture, Nutrient Status and Root Growth of Radiata Pine

The influence of soil texture on root growth is indirect. Root growth is directly affected by those physical (and chemical) properties that vary with soil texture (soil water, soil air and soil strength) (Ike, 1970; Askew and Moffat, 1970). A more recent review by Glinski and Lipiec (1990) concluded that: 1). Generally, root growth is reduced more in soil of coarse texture than in finer texture due to lower fertility, lower unsaturated hydraulic conductivity and lower water storage capacity; 2). The soil texture influences root systems more indirectly, its influence is realised by creating soil mechanical impedance (soil strength) to root penetration, modifying the water and aeration status, nutrient content and availability.

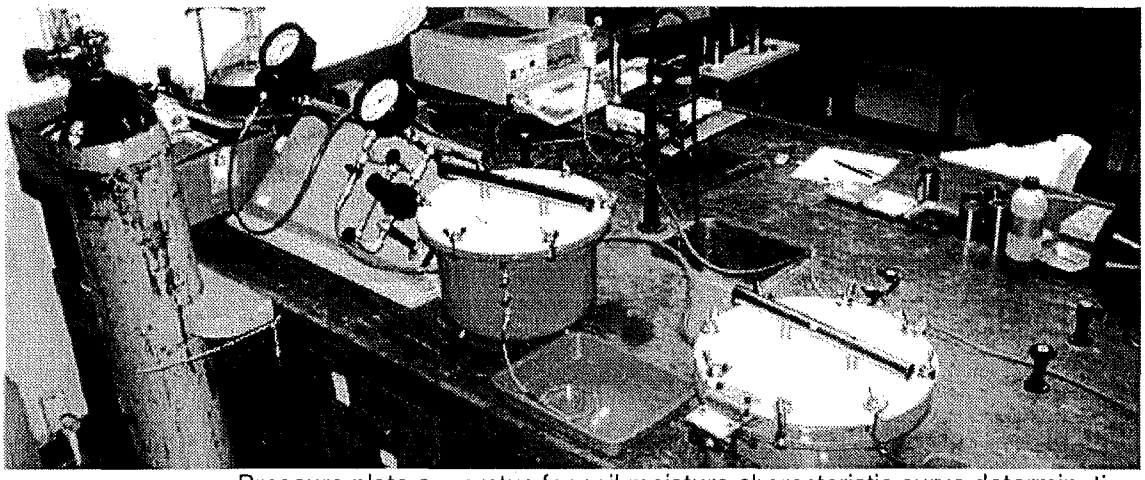
From the soils nutrition report from N.Z. Forest Research Ltd (Appendix 1), the ash and argillite have adequate essential nutrients while pumice and clay are critically deficient in several of the key nutrients necessary for growth of radiata pine. However these comments are given for the normal plantation practices and it might be different for seedlings growing for a short period.

Penfold (1998) carried out an experiment to investigate the influence of the above mentioned soil types and nutrient addition on root growth of radiata pine. He concluded that: 1). There was insignificant effect from soil texture on the primary root growth of radiata pine seedlings when other physical properties were non-limiting; 2). The effect of nutrient addition on primary root growth of radiata pine seedlings during the first 12 days of establishment was insignificant when soil physical properties were uniform and non-limiting.

All these conclusions strongly suggest that soil textures can be used as a medium to test the relationship between the three basic soil physical properties (matric potential, soil strength and air-filled porosity) and root growth without complication from soil texture itself. In the case of primary root growth for less than two weeks, even the original nutrient status of these soil textures will not have a significant effect on the root growth.

CHAPTER 4

SOIL PHYSICAL PROPERTIES AND INTERACTIONS



Pressure plate apparatus for soil moisture characteristic curve determination

4.1 Abstract

Soils of contrasting textures were repacked to a range of bulk densities to test the relationship between soil matric potential, soil strength and soil air-filled porosity (dependent variables) and soil volumetric water content and soil bulk density (independent variables) in the laboratory using pressure plate apparatus and a cone penetrometer.

When a saturated soil (θ_s) is drying, both soil volumetric water content (θ_v) and soil matric potential (Ψ_m) decrease, and soil air-filled porosity (ε_a) and soil strength (Q) increase. The relationship between soil matric potential and volumetric water content

(the soil moisture characteristic curve) can be represented by an non-linear model ($\Psi_m = - a (\theta_v/\theta_s)^{-b}$. In all soils most water was held at high potentials and 60% - 70% of available water capacity (AWC) was held between - 0.01 and - 0.20 MPa soil matric potential. The relationship between soil strength (Q) and volumetric water content was described by a logarithmic model ($Q = a \ln\theta_v + b$).

Air filled porosity was calculated from soil bulk density (ρ_b) and soil particle density (ρ_s) from the relationship $\varepsilon_a = 1 - \theta_v - \rho_b / \rho_s$.

When soils were compacted (increased in bulk density), the total amount of water held in the soil at field capacity (-0.01MPa matric potential) increased in all soils, particularly in the coarser soils. Usually, this also increased the amount of available water capacity (between – 0.01 and – 1.5 MPa matric potential), but in the finer textured soils, the amount of available water capacity might have no change and even a slight decrease at high bulk densities. For the same amount of water loss, both the suction and soil strength increased faster in the fine textured soils than in the coarse textured soils.

At a given matric potential, soil air-filled porosity in pumice and ash were higher than in argillite and loess due either to their coarse texture (pumice) or high organic matter (ash). However, in all of the soils between – 0.01 and – 1.5 MPa matric potential, air filled porosity was mostly above the value 0.10 $cm^3 cm^{-3}$ that is normally believed to be suitable for the root growth of most species. Therefore, these soils can be used in later experiments to look at the interacting effects of matric potential and soil strength on root growth without any effect of soil aeration.

Key Words: Soil matric potential; soil strength; soil air-filled porosity; soil moisture characteristic curve; soil strength characteristic curve; soil bulk density

4.1 Introduction

The soil physical environment in which plants grow is a dynamic system. Root growth in this system is a process of continuous adjustment and adaptation, either actively or passively. Soil matric potential (Ψ_m), soil strength (Q), soil air-filled porosity (ε_a) and soil temperature are the three most important soil physical properties directly determining root growth (Letey, 1985).

The soil physical properties include soil colour, soil particle density (ρ_s), soil organic matter content, soil texture, soil bulk density (ρ_b), soil volumetric water content (θ_v), soil temperature, soil air and soil strength. Soil colour, soil particle density, soil organic matter content, and soil texture are related to a particular soil type and vary spatially but not temporally on a shorter time scale. Soil bulk density varies spatially but also varies temporally when soils swell or shrink or when soils are compacted from cultivation or harvesting equipment. The effects of changing soil bulk density can best be described in terms of changes in soil water, soil air and soil strength. Soil water content (and potential), soil air, soil strength and soil temperature vary both spatially and temporally and it is these physical properties that are the most dynamic in the soil and which are the most important in determining root growth. A decrease in soil water content increases both soil aeration and soil strength, and an increase in soil bulk density increases soil strength, decreases soil air-filled porosity and may increase or decrease soil water retention depending on soil texture and the initial bulk density.

When water content decreases, soil matric potential decreases too. The relationship between soil matric potential and soil volumetric water content is normally called the soil moisture characteristic curve or the soil moisture retention curve. Several empirical equations have been proposed to describe soil moisture characteristic curves for some soils and within limited matric potential ranges (Hillel, 1980). A widely used analytic model for the soil moisture characteristic curve is the Brooks-Corey power-function

(Brooks and Corey, 1964). A simpler form of this function was given by Cosby *et al.* (1984) and Campbell (1985) as:

$$\Psi_m/\Psi_e = (\theta_v / \theta_s)^b \text{ for } \Psi_m < \Psi_e \quad (4.1)$$

where Ψ_m is soil matric potential (- MPa), θ_v is volumetric water content (= θ_s at saturation), Ψ_e and b are adjustable parameters.

Buchan and Grewal (1990) used the log-transformation of Model 4.1 (Model 4.2) and demonstrated that Model 4.2 gave a good fit to observations over varying ranges of soil matric potential.

$$\ln |\Psi_m| = a + b\ln (\theta_v/\theta_s) \quad (4.2)$$

In this study, model 4.2 will be tested using sieved and repacked soils of different textures to describe the relationship between soil matric potential and soil volumetric water content.

When soil is drying, soil strength increases. Khristov and Khristov (1981) reported that at constant bulk density, a linear relationship existed between soil strength and soil volumetric water content. In this study, both linear and non-linear models will be used to test the relationship between soil strength and soil volumetric water content.

Soil air-filled porosity is a function of soil particle density, soil bulk density and soil volumetric water content. In the case of a nonswelling soil, the air-filled porosity decreases in a linear manner with an increase in soil volumetric water content, and in a swelling soil, the relationship becomes non-linear (Glinski and Lipiec, 1990).

When soil is compacted, the soil moisture characteristic curve, the soil strength characteristic curve and soil air-filled porosity and their interactions will be subject to change, and the details of these changes in the selected four soils remain unknown.

The objective of the work described in this chapter was to measure the interactions between soil water, soil air and soil strength in the four soils characterised in Chapter 3 at a range of bulk densities. These relationships will then be used in experiments following to determine the effect of these interacting soil physical properties on root growth.

4.2 Materials and Methods

The four soil textures described in Chapter 3 were used in this study (see Chapter 3 for details). The sieved soils were repacked into a stainless steel ring (48 mm internal diameter, depth 15 mm) to a given bulk density. The weight of wet soil required for each ring was calculated by:

$$W = 27.14 \times \rho_b \times (1 + \theta_g) \quad (4.3)$$

where W = weight of wet soil required (g)

ρ_b = soil bulk density (g cm^{-3})

θ_g = gravimetric soil water content (g cm^{-3})

Soils were uniformly packed into the steel tube from both ends to achieve a homogenous bulk density distribution both vertically and horizontally using the packing technique described by Misra and Li (1996). There were three bulk density treatments for each soil and three replicates for each treatment.

4.2.1 Determination of Bulk Density Range for Each Soil Texture

The choice of the bulk density range for each soil depended on their shrinking and swelling properties. All four soils used in this experiment have low swelling and shrinking properties (Table 3.2). The lowest bulk density for each soil represented a no or slight compaction condition where no serious shrinking occurred during drying. The highest bulk density represented moderate to severe compaction where there was no serious swelling when the soil was saturated. Between these two extremes, a medium value for soil bulk density was decided. Although the loess is considered to be non-shrinking silty clay, a slight shrinking was observed at water potentials lower than -1.0 MPa. Calculations of volumetric water content and air-filled porosity for the loess had taken the corresponding soil volume reduction into account.

4.2.2 Soil Matric Potential Establishment

Repacked soil samples were placed in a water bath to saturate overnight. The saturated soil samples were placed in a pressure plate apparatus to equilibrate at selected water potentials by the method described by Merwe (1990). After equilibration at each matric potential, the samples were weighed immediately to calculate θ_v at this matric potential value. This process was repeated at seven matric potential levels: -0.01MPa, -0.03 MPa, -0.07MPa, -0.1MPa, -0.2MPa, -0.5MPa and -1.5 MPa. The time for equilibrium ranged from 1-2 days for -0.01 M Pa to about 4 weeks for -1.5 MPa.

4.2.3 Soil Strength Determination

Immediately following the volumetric water content determination, the equilibrated samples were used to determine soil strength by a custom-designed laboratory cone penetrometer *(appendix 6). This penetrometer had a constant speed/variable torque motor that pushed the metal probe into the soil sample at a constant speed of 3 mm min^{-}

* Designed by R. Misra and manufactured by Precision Engineering, Australia

[1]. The force generated from the probe was measured by an electronic balance and recorded every 10 seconds (each 0.5 mm depth) and transferred to an Excel worksheet using the Software Wedge*. In this study, the metal probe had a cone base diameter of 2 mm and a tip semi-angle of 30 degrees. The soil strength was calculated from the following equation:

$$Q = F/\pi r^2 = Wt \times g / \pi r^2 \quad (4.4)$$

where Wt = force measured by electronic balance (kg)

g = gravitational acceleration = 9.8 m s^{-2}

r = radius of the cone base of metal probe (mm)

The soil strength was taken as the mean of 5 soil strength values recorded between 1cm and 1.25 cm depth (The reason for this will be explained in 6.4.1).

6.5.2.

4.2.4 Determination of Soil Air-filled Porosity

Aeration is quantitatively represented by the air-filled porosity (ε_a) calculated by Equation (4.5):

$$\varepsilon_a = 1 - \theta_v - \rho_b / \rho_s \quad (4.5)$$

where θ_v = volumetric water content ($cm^3\ cm^{-3}$)

ρ_b = soil bulk density ($g\ cm^{-3}$)

ρ_s = particle density ($g\ cm^{-3}$)

4.2.5 Statistical Analysis

The measured volumetric water content data at each water potential was used to fit the linear regression model given by Buchan and Grewal (1990) (Equation 4.2). A non-

* T.A.L Enterprises

linear modelling approach (NLIN Proc, SAS v 6.12) was used to fit a relationship between soil strength and volumetric water content using the residual of mean square (RMS) as a model selection criterion.

4.3 Results

4.3.1 Choice of Bulk Density Range for Four Soil Types

Pumice was a coarse loamy sand and the ash a sandy clay loam in texture. Both had low particle densities. The low values for the pumice were due to the low particle density of the mineral phase and the low particle density for the ash was due to its high organic matter content (Chapter 3). Therefore, both the pumice and the ash had lower natural ranges of bulk density than the argillite and loess and lower values of bulk density for a particular soil strength. The choice of bulk densities to achieve a common soil strength range over all the soils is given in Table 4.1. Even though the bulk density ranges were different between soils, the three bulk densities for each soil could be qualitatively described as low, medium and high for comparison between soils.

Table 4.1. Choice of soil bulk densities (ρ_b) for four soil textures. √ is the bulk density selected for each texture, L = low, M = medium and H = high

ρ_b (g cm^{-3})	Pumice	Argillite	Ash	Loess
0.7	√ (L)		√ (L)	
0.75				
0.8	√ (M)		√ (M)	
0.85	√ (H)		√ (H)	√ (L)
0.9		√ (L)		
0.95				√ (M)
1		√ (M)		
1.05				√ (H)
1.1		√ (H)		

4.3.2 Soil Moisture Characteristic Curves

All the data were satisfactorily fitted to the linear regression model of Buchan and Grewal (1990). All regressions had $p < 0.001$ and the sample size (n) and R^2 are given in Table 4.2:

Table 4.2. Regression models between soil matric potential (Ψ_m) and volumetric water content (θ_v) for soils of contrasting textures at three bulk density levels

Soil Type (Texture)	ρ_b (g cm^{-3})	Soil Moisture Characteristic Curves $\ln \lvert\Psi_m\rvert = a + b\ln(\theta_v/\theta_S)$ ($p < 0.0001$, n = 21, SE = standard error)
Pumice (loamy sand)	0.7	a = - 8.77, b = -4.47 (SE = 0.11), R^2 = 0.99
	0.8	a = -8.27, b = -4.77 (SE = 0.17), R^2 = 0.98
	0.85	a = -7.76, b = -4.79 (SE = 0.16), R^2 = 0.98
Argillite (loam)	0.9	a = - 7.76, b = -6.50 (SE = 0.24), R^2 = 0.97
	1.0	a = - 6.86, b = -6.78 (SE = 0.24), R^2 = 0.98
	1.1	a = -5.86, b = - 7.04 (SE = 0.22), R^2 = 0.98
Ash (sandy clay loam)	0.7	a = -9.13, b = -4.97 (SE = 0.19), R^2 = 0.98
	0.8	a = -8.76, b = -5.58 (SE = 0.25), R^2 = 0.96
	0.85	a = -8.64, b = -6.46 (SE = 0.44), R^2 = 0.93
Loess (silty clay)	0.85	a = -10.59, b = -10.08 (SE = 0.35), R^2 = 0.98
	0.95	a = -9.91, b = -12.06 (SE = 0.51), R^2 = 0.97
	1.05	a = -7.99, b = -13.05 (SE = 0.67), R^2 = 0.95

The lower the value of b in the regressions the harder it is to extract water from the soil at a given water content (ie the greater suction). The b values were in the order pumice > ash > argillite > loess, in the same order of texture from coarse to fine. The b value decreased with increasing bulk density in all soils. At the same soil volumetric water content, the matric potential in compacted soil was lower than in less compacted soil.

The moisture characteristic curves in Table 4.2 can be re-written into the power form (Equation 4.1) and the response of matric potential change to each unit of water loss is demonstrated in Figure 4.1.

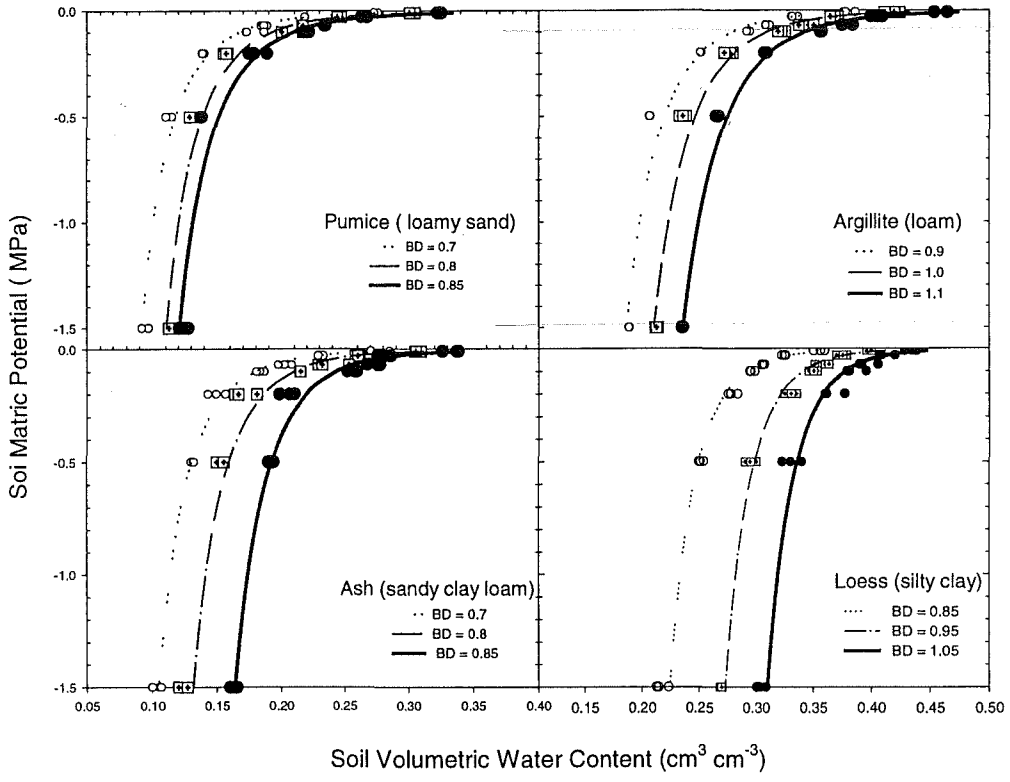


Figure 4.1. Relationship between soil matric potential (Ψ_m) and volumetric water content (θ_v) for four soil textures at three bulk densities (BD = ρ_b)

4.3.3. Soil Strength Characteristic Curves

The relationship between soil strength and volumetric water content was established for each of the three bulk densities of the four soil types. Volumetric water contents were between field capacity and wilting point (Figure 4.2).

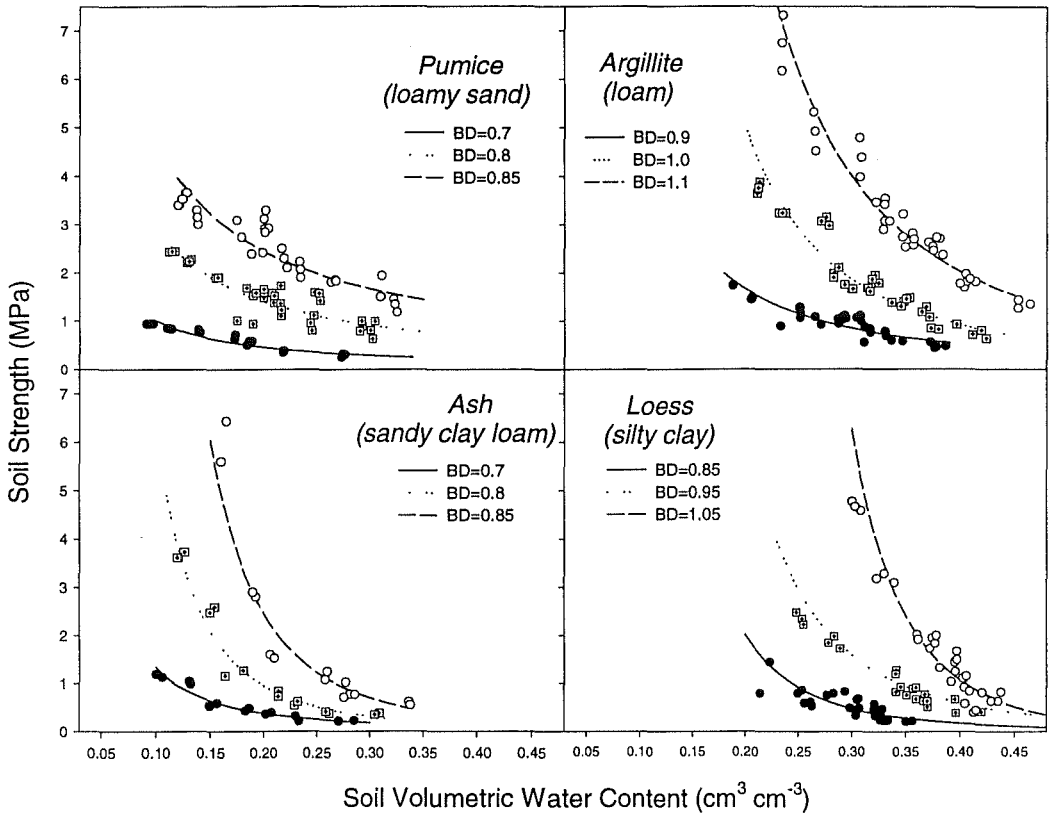


Figure 4.2. Relationship between soil strength (Q) and volumetric water content (θ_v) for four soil textures at three bulk densities (BD = ρ_b)

Soil strength increased as soil water content decreased (Figure 4.2). This relationship was more complicated than the simple linear relationship suggested by Khristov *et al.* (1981). By using SAS non-linear regression, the original data were best fitted by a logarithmic model:

$$Q = a\ln\theta_v + b \qquad (4.6)$$

where Q is soil strength (MPa), θ_v is soil volumetric water content ($cm^3\ cm^{-3}$), a and b are regression coefficients.

a and b were constant at a given bulk density for a given soil type, but changed both with soil type and bulk density (Table 4.3).

Table 4.3. Parameters for the logarithmic model between soil strength (Q) and volumetric water content (θ_v) for soils of contrasting textures at three bulk density levels (ρ_b) (S.E. = standard error; RMS = Residual Mean Squares)

Soil Type (Texture)	BD	Estimated Parameters	S.E.	RMS	θ_v range
Pumice (loamy sand)	0.7	a = -0.674 b = -0.639	0.043 0.076	0.0061	0.09 - 0.28
	0.8	a = -1.584 b = -1.056	0.142 0.232	0.0591	0.11 - 0.31
	0.85	a = -2.173 b = -0.946	0.17 0.27	0.0778	0.12 - 0.33
Argillite (loam)	0.9	a = -1.654 b = -1.095	0.107 0.138	0.0167	0.19 - 0.39
	1	a = -4.632 b = -3.497	0.235 0.277	0.072	0.21 - 0.43
	1.1	a = -7.955 b = -5.302	0.358 0.386	0.1471	0.24 - 0.47
Ash (sandy clay loam)	0.7	a = -1.024 b = - 1.211	0.093 0.1648	0.0123	0.10 - 0.28
	0.8	a = - 3.360 b = -4.108	0.554 0.867	0.2562	0.13 - 0.31
	0.85	a = -6.613 b = - 7.503	1.076 1.562	0.9156	0.16 - 0.34
Loess (silty clay)	0.85	a = -1.999 b = -1.864	0.266 0.318	0.0223	0.22 - 0.36
	0.95	a = - 4.116 b = -3.311	0.567 0.587	0.0874	0.27 - 0.41
	1.05	a = - 11.08 b = -8.961	0.793 0.748	0.0978	0.31 - 0.45

a represents the rate of increase in soil strength with the natural log of volumetric water content. The value of a was influenced more by bulk density than soil type. This means that the rate of increase in soil strength as soil dries is more sensitive to changes in bulk density in a given soil, than to changes in soil type or texture. For a given soil, a decreased with increasing soil bulk density (Table 4.3). The rate of increase in soil strength with decreasing soil water content increased with increasing bulk density (Figure 4.2). For each of low, medium and high bulk density (Table 4.1), a was mostly in the order loess < argillite < ash < pumice. This means that the rate at which soil strength increased with decreasing water content increased as the soils became finer in texture.

4.3.3 Soil Air-filled Porosity and Volumetric Water Content

In a given soil, soil particle density is constant. At given bulk density, soil air-filled porosity (ε_a) is a linear function of soil volumetric water content (θ_v). The change of soil air-filled porosity with soil volumetric water content can be calculated by Equation 4.5.

Based on Equation 4.5, the equations connecting ε_a and θ_v for each soil at different bulk densities were established, and air-filled porosities at field capacity (ε_{afc}) and wilting point (ε_{awp}) were calculated and are listed in Table 4.4.

At field capacity, ε_a ranged from just less than 0.10 $cm^3\ cm^{-3}$ in argillite (ρ_b = 1.1) to 0.43 $cm^3\ cm^{-3}$ in pumice (ρ_b = 0.70) and at wilting point from 0.27 in loess (ρ_b = 1.05) to 0.62 in pumice (ρ_b = 0.7).

Table 4.4. Relationship between soil air-filled porosity (ε_a) and volumetric water content (θ_v) at three bulk density levels. ε_{afc} is soil air-filled porosity at field capacity and ε_{awp} is soil air-filled porosity at wilting point

Soil Type (Texture)	ρ_b (g cm^{-3})	$\varepsilon_a = 1 - \theta_v - \rho_b / \rho_s$	$\varepsilon_{a\,fc}$	$\varepsilon_{a\,wp}$
Pumice (loamy sand)	0.7	0.714 - θ_v	0.435	0.622
	0.8	0.673 - θ_v	0.364	0.562
	0.85	0.652 - θ_v	0.319	0.531
Argillite (loam)	0.9	0.647 - θ_v	0.253	0.461
	1	0.608 - θ_v	0.176	0.398
	1.1	0.569 - θ_v	0.096	0.334
Ash (sandy clay loam)	0.7	0.709 - θ_v	0.425	0.604
	0.8	0.668 - θ_v	0.357	0.536
	0.85	0.647 - θ_v	0.307	0.483
Loess (silty loam)	0.85	0.663 - θ_v	0.299	0.439
	0.95	0.624 - θ_v	0.212	0.351
	1.05	0.584 - θ_v	0.138	0.274

4.4. Discussion

4.4.1 Available Water Capacity in Compacted Soils

The coarser soils (pumice, ash) had lower values of volumetric water content at field capacity and wilting point, higher corresponding values of air-filled porosity and higher values of available water capacity (AWC, the difference between water contents at field capacity and wilting point) than the finest soil texture (loess) (Table 4.5). Soil of medium texture (argillite) had the highest AWC. In addition, the coarser soils had a greater proportion of water held at at higher potentials ($\theta_{0.01\text{-}0.2}$/ θ_{fc}) and a higher percentage of available water capacity in total water holding capacity (AWC/θ_{fc}).

Table 4.5. Soil water holding capacity and available water capacity in compacted soils of four soil textures. ρ_b = bulk density (g cm^{-3}), θ_{fc} = volumetric water content at field capacity (cm^3 cm^{-3}), θ_{wp} = volumetric water content at wilting point (cm^3 cm^{-3}), AWC = available water capacity(cm^3 cm^{-3}), $\theta_{0.01\text{-}0.2}$ = water held between -0.01 to -0.2 MPa

Soil Type	Pumice (loamy sand)			Argillite (loam)			Ash (sandy clay loam)			Loess (silty clay)		
ρ_b	0.70	0.80	0.85	0.90	1.00	1.10	0.70	0.80	0.85	0.85	0.95	1.05
θ_{fc}	0.280	0.310	0.335	0.395	0.435	0.475	0.280	0.315	0.340	0.365	0.415	0.450
θ_{wp}	0.092	0.111	0.121	0.186	0.210	0.235	0.105	0.132	0.164	0.224	0.273	0.310
AWC	0.187	0.198	0.213	0.208	0.222	0.238	0.179	0.180	0.176	0.140	0.139	0.137
AWC/θ_{fc}	0.670	0.642	0.638	0.528	0.514	0.502	0.631	0.578	0.518	0.384	0.338	0.306
$\theta_{0.01\text{-}0.2}$	0.130	0.145	0.155	0.145	0.155	0.165	0.125	0.130	0.120	0.095	0.095	0.090
$\theta_{0.01\text{-}0.2}/\theta_{fc}$	0.460	0.470	0.460	0.370	0.360	0.350	0.450	0.410	0.350	0.260	0.230	0.200
$\theta_{0.01\text{-}0.2}$/ AWC	0.690	0.730	0.720	0.690	0.690	0.690	0.710	0.700	0.670	0.680	0.630	0.620

When a soil was compacted (increased in bulk density) it behaved mainly as though it were of finer texture, i.e. it had higher values of water content at field capacity and wilting point, and correspondingly reduced air-filled porosities (Table 4.4 and Table 4.5). The available water capacity (AWC) and the percentage of available water capacity to total water capacity (AWC/θ_{fc}) were higher in the two coarse soils than in the finest texture soil. Increasing bulk density increased the available water capacity (AWC) for the coarser textured soils, the pumice and the argillite, and had little effect on the proportion of water held at higher potentials ($\theta_{0.01\text{-}0.2}/\theta_{fc}$). By contrast, the available water capacity was largely unchanged for the ash and was actually decreased for the loess and the proportion of water held at higher potentials ($\theta_{0.01\text{-}0.2}/\theta_{fc}$) was decreased. Even so, most plant available water was held at high potentials. More than 60% of available water capacity ($\theta_{0.01\text{-}0.2}$/ AWC) was held in between -0.01 and - 0.2 MPa in all four soil textures (Table 4.5).

4.4.2 Implications for Management

When soil is compacted, the soil strength increases, and the rate of increase in soil strength is related to the clay component and is associated with soil water content (Smith *et al.*, 1997). Table 4.6 gives the soil strengths of the pumice and loess at - 0.01 MPa and - 1.5 MPa matric potential.

Table 4.6. Interaction of soil strength and soil water content in soils of contrasting textures. ρ_b = bulk density (g cm^{-3}), Q_{fc} = soil strength at field capacity (MPa), Q_{wp} = soil strength at wilting point (MPa)

Soil Type (Textures)	ρ_b	Q_{fc}	Q_{wp}
Pumice (loamy sand)	0.7	0.48	0.98
	0.8	0.89	2.44
	0.85	1.65	3.66
Loess (silty clay)	0.85	0.35	1.16
	0.95	0.46	2.08
	1.05	0.78	5.14

The relationship between soil strength, texture and bulk density is complex. When soil bulk density of pumice increased from low to medium (from 0.7 to 0.8), both Q_{fc} and Q_{wp} increased about 2 times (from 0.48 to 0.89 MPa and 0.98 to 2.4 MPa respectively). However, when bulk density increased from low to medium (from 0.85 to 0.95) in loess, Q_{fc} and Q_{wp} of loess increased only from 0.35 to 0.46 and 1.16 to 2.08 MPa respectively. Increase of bulk density has a greater effect of increasing soil strength in the coarse soil than in fine soil but decrease of soil water content has a greater effect on increasing soil strength in fine soil texture than in coarse texture soil. At both low and

high bulk densities, the finer loess had lower soil strength than the coarser pumice at field capacity but higher soil strength at wilting point. This suggests that clay content is negatively associated with soil strength at high water content but positively associated with soil strength at low water content. Smith *et al.* (1997) also reported soil strength at wilting point (-1.5 MPa) increased with increasing clay content. In addition, the results reported here have shown that drying soil will cause greater increases in soil strength in an already high strength soil (high bulk density) than in a lower strength soil (lower bulk density) particularly in finer soils. Conversely, watering a dry compact soil will cause a greater reduction in soil strength than watering a relatively non-compact soil, and particularly a fine soil.

The practical implications are that traffic will compact coarse soil to values of soil strength that do not differ greatly with soil water content. Adding water to a dry coarse soil will do little to reduce soil strength. The reduction of soil strength in coarse compacted soils can be achieved best by reducing soil bulk density by mechanical means. In fine textured clay soil, traffic ideally should be confined to dry soils where the soil strength is already high and therefore will therefore resist compaction. The high soil strength will be reduced when the soil is wet.

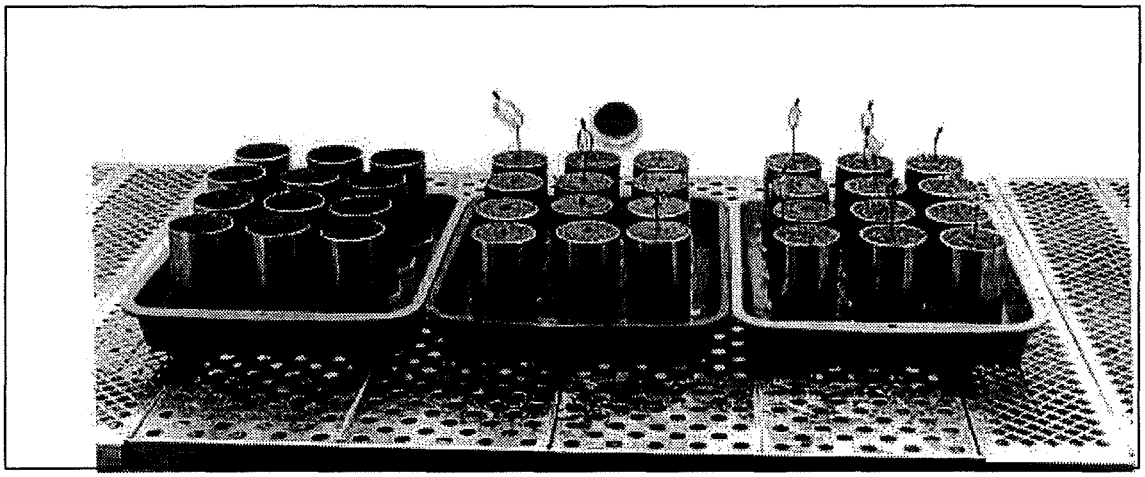
4.4.3 Soil Aeration

It has been widely accepted that air-filled porosity will only inhibit plant growth at value < 0.10 cm^3 cm^{-3} (Sands and Bowen, 1978, Theodorou *et al.*, 1991; Xu *et al.*, 1991). The lowest air-filled porosity recorded in this study at field capacity was 0.096 cm^3 cm^{-3} in the argillite at high bulk density (Table 4.4) and all other values were above 0.10 cm^3 cm^{-3}. On this basis it was expected that the experiments on root growth described in later chapters using these soils would not be complicated by limiting aeration. Sands and Bowen (1978) concluded that the reduced root penetration of radiata pine in compacted sandy soil was probably due to the greater resistance offered by soils of higher strength to root penetration rather than to reduced aeration. Results from this experiment at least partially support this conclusion since the air-filled

porosity remains reasonably high even at the high bulk density for the four experimental soils. A recent study of Penfold (1998) using ash, argillite and loess soils has questioned the validity of the critical threshold value of 0.10 cm^3 cm^{-3} and the implications of this will be discussed in further chapters.

CHAPTER 5

INFLUENCE OF WATER POTENTIAL ON ROOT GROWTH OF PINUS RADIATA SEEDLINGS



5.1 Abstract

The influence of water potential on root growth of radiata pine (*Pinus Radiata* D. Don) seedlings was investigated both in soil and solution medium in this study. At high water potentials (> -0.20 MPa), root elongation rate decreased linearly with decrease of soil matric potential at constant soil strength and non-limiting air-filled porosity. When water potential was lower than – 0.20 MPa, the decreasing of root growth rate was observed to slow down and was linearly related to the log of the absolute value of water potential (ln |Ψ|).

Over the whole water potential range of agronomic interest (-0.01 to –1.5 MPa), the effect of water potential on root growth might include two different processes. At higher water potential (> -0.20 MPa), the effect of water potential on root growth was mainly a physically pressure adjustment. Further water stress (below -0.20 MPa water potential) might incur a series of physiological processes that would partially compensate the detrimental effect from water stress.

Root growth in soil was an integrated effect of both soil matric potential and soil strength and change of water potential affected root growth more at low soil strength than at high soil strength.

Key Words: *Pinus radiata* D. Don; soil matric potential; root elongation rate; air-filled porosity; soil strength

5.2 Introduction

Root growth in soil has been widely reported to decrease as soil matric potential decreases over the water potential range of agronomic interest between - 0.01 to -1.5 MPa (Hillel, 1979; Kramer, 1983; Costantini *et al.*, 1996a). This may be due to decreased water potential, increased soil strength, or both. Mirreh and Ketcheson (1973) reported that root growth rate in corn was reduced in media at constant strength when the soil water potential was reduced. Costantini *et al.* (1996a) reported that radicle elongation of *Pinus caribaea* var *hondurensis* after 48 hours of growth decreased monotonically to zero as matric potential decreased from -0.0065 to - 3.13 MPa on filter paper. In contrast, Greacen and Oh (1972) found that pea roots could osmo-regulate to maintain turgor over a range of soil water potential from - 0.28 to - 0.80 MPa, and consequently that root penetration was determined solely by soil strength and was independent of soil water potential.

Effort to establish the relationship between matric potential and root growth in soil has not been conclusive mostly because of the difficulty in isolating the effect of matric potential from the interacting effects of soil strength and soil aeration (Yapa *et al.*, 1988). Costantini *et al.* (1996a) found there was an optimal level of matric potential for radicle elongation in soils. At matric potential above or below the optima, inadequate air-filled porosity and moisture stress respectively adversely impacted upon elongation.

Soil texture influences root systems more indirectly, creating mechanical impedance of the soils, modifying their water and aeration status, nutrient content and availability (Glinski and Lipiec, 1990). Penfold (1998) found that root growth of radiata pine was not directly affected by soil texture itself, but rather by the soil water, soil strength and soil air relationships that are associated with soil texture. He also found no significant effect of soil air when air-filled porosity was larger than 0.16 cm^3 cm^{-3} in repacked soil.

The aim of the study reported in this chapter was to isolate the effect of soil water potential from soil strength and soil air on root growth of radiata pine seedlings, as preliminary data required for building a model of root growth in soils. Two experiments were included in this study.

Experiment I: A relatively narrow water potential range (from - 0.01 to - 0.2 MPa) was established at nearly constant values of soil strength and non-limiting air-filled porosity using soils of different textures to test the quantitative relationship between soil matric potential and root elongation rate.

Experiment II: Seedlings of radiata pine were grown in rooting medium of Polyethylene Glycol 4000 (PEG 4000) (Appendix 3) and Mg5/K20 combination nutrient (Appendix 4) to test the response of root growth to the whole water potential range (-0.01 to –1.5 MPa) of agronomic interest.

In order to get the fine degree of control over establishment of matric potentials and to

minimise any subsequent water loss in soil, pre-germinated seeds (non-transpiring tissue) were used in the soil experiment and over a short growing period (no longer than seven days). However it is technically difficult to hold a pregerminated seed in a solution rooting medium; therefore seedlings with 20 mm radicles were used in the solution experiment. It is possible the root elongation rates will be different due to the different ages of the plants in the soil and solution experiments. Therefore, the absolute values of root elongation rates measured in the soil experiment and the solution experiment should not be directly compared. (The same applies for the soil and solution experiments in Chapter 7).

5.3 Materials and Methods

5.3.1 Experiment I: Root Growth and Soil Matric Potentials

5.3.1.1 Establishment of Soil Matric Potentials at Constant Soil Strength

Based on soil moisture characteristic curves and soil strength characteristic curves (Chapter 4), five soil matric potential levels (-0.01, -0.03, -0.07, -0.1, and -0.2 MPa) were established at soil strength levels close to target levels of 0.5 and 1.5 MPa using soils of contrasting textures and bulk densities, all at air-filled porosities > 0.14 cm^3 cm^{-3} (Table 5.1):

Soils of corresponding texture were then uniformly packed to the required bulk density in 100 mm long, 48 mm ID stainless steel tubes. The packing techniques of Misra and Li (1996) were used to minimise variation in soil bulk density with depth. The packed soil samples were equilibrated from saturation to - 0.01, - 0.03, - 0.07, - 0.1, and - 0.2 MPa in a pressure plate apparatus. The volumetric water content was determined immediately at equilibrium and air-filled porosity was calculated as described in 4.2.4. The actual soil strength of the equilibrated soil samples was measured using a cone penetrometer as described in 4.2.3 and samples with soil strength outside the target level

± 10% were discarded. There were three replicates for each value of matric potential at each target strength level.

Table 5.1. Soil strength and air-filled porosities at given soil matric potentials calculated from soil moisture characteristic curves and soil strength characteristic curves. ρ_b = bulk density (g cm^{-3}), Ψ_m = soil matric potential (-MPa), ε_a = air-filled porosity (cm^3 cm^{-3}) and Q = soil strength (MPa)

Q (MPa)	Soil Type	ρ_b	Ψ_m (MPa)	ε_a calculated	Q calculated
	Argillite	0.90	-0.01	0.290	0.60
	Ash	0.80	-0.03	0.410	0.45
Target 0.5	Loess	0.85	-0.07	0.361	0.53
	Ash	0.70	-0.1	0.530	0.55
	Pumice	0.70	-0.20	0.570	0.57
	Argillite	1.10	-0.01	0.144	1.50
	Argillite	1.0	-0.03	0.263	1.44
Target 1.5	Loess	1.05	-0.07	0.197	1.55
	Pumice	0.80	-0.10	0.480	1.55
	Ash	0.80	-0.20	0.482	1.54

5.3.1.2 Pre-germination of Seeds and Planting in Soils

Radiata pine seeds* with a weight of 0.004 g ± 0.0005 g were immersed in distilled water overnight and then placed on saturated filter papers treated with fungicide# in a petri dish. The filter papers were watered every day to maintain the moisture of the

* The seeds used in this experiment were GF-17 and were kindly contributed by ***Proseed New Zealand***

Thiram (T.M.T.D), Arthur Yates & CO, LTD, New Zealand

seed. It normally took seven days until most seeds started to germinate. Germinated seeds with 2 mm radicles were chosen for planting.

Pregerminated seeds then were planted into the repacked soil in the steel tubes. The soil surface was divided into four quadrants (Figure 5.1).

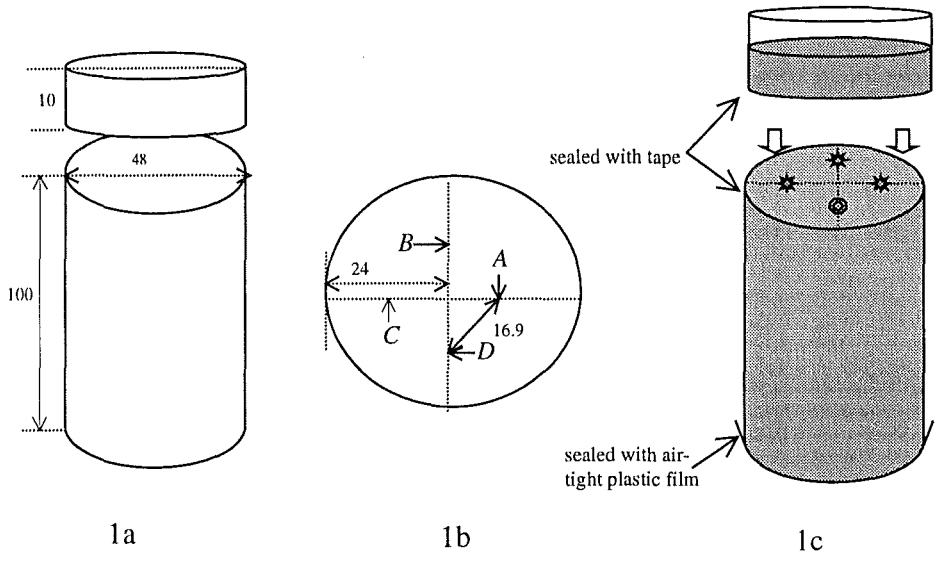


Figure 5.1. Design of stainless steel tube and seedling planting. The stainless steel tube was 100 mm in length and 48 mm in inner diameter (Figure 5.1a). The soil surface was evenly divided into four equal quadrants (Figure 5.1b). Positions A, B and C were used to plant seedlings and position D was used to determine the soil strength. A 10 mm long, 48 mm inner diameter ring was attached to the top of the tube and packed with soil of the same texture to a depth of 6 mm (Figure 5.1c).

The penetrometer measurement was made at position D. Pre-germinated seeds were planted at positions A, B, and C. Soil of the same texture was packed to the same bulk density to a depth of 6 mm in a 15 mm length stainless steel ring and taped above the seeds to assist in controlling water loss over the seven days of experiment. The bottom of the tube was sealed with airtight plastic film. The seedlings were grown in the tubes for 7 days in a controlled environment cabinet (light period: 20 ^{0}C, 12 hours, 80% relative humidity, 700 μm m^{-2} s^{-1} photosynthetically active radiation; dark period: 17 ^{0}C,

12 hours, 80% relative humidity). At harvest the average soil volumetric water content was determined, then the soil air-filled porosity and soil strength were calculated as described above. At harvest, seedlings were carefully removed from the tubes and washed clean of soil. The seedling length, root length and shoot length were measured with a scale, and root and shoots were then oven dried at 70^0C for 72 hours to determine biomass. The average of the three seedlings in each pot was used for the analysis.

5.3.2 Experiment II: Response of Root Growth to Water Potential to the Whole Water Potential Range of Agronomic Interest (–0.01 to – 1.5 MPa)

5.3.2.1 Establishment of Rooting Medium

Pre-germinated radiata pine seeds (see 5.3.1) were planted in a sand bed. It took about 4 days until the root was about 20 mm long. These seedlings were transferred into Mg5/K20 combination nutrient solution with 8.3 mg/l nitrogen (water potential is equal to -0.01 MPa) to grow until the needles of the seedlings were fully opened. The length of root and shoot was measured (the root and shoot was separated by the root collar and was marked with a water resistant ink pen). PEG 4000 was added to Mg5/K20 nutrient solutions containing 8.3 mg/l nitrogen (Appendix 4) to obtain rooting medium of -0.01, -0.03, -0.07, -0.1, -0.2, -0.5, -1.0, -1.5 MPa water potentials (Appendix 3). These seedlings were then transferred into a 500ml plastic pot containing rooting medium at the range of water potentials described above. Three seedlings were anchored separately into the 3 of the 4 pre-drilled 1.2 mm ID holes on the lid with Blue Tak re-usable adhesive*. The fourth hole at the centre was left as an air-escape. A 5 mm ID hole was drilled for an air-pump hose. All the pots were connected to a pumping system to maintain ideal aeration (Figure 5.2).

* Bostik (New Zealand) Pty Ltd

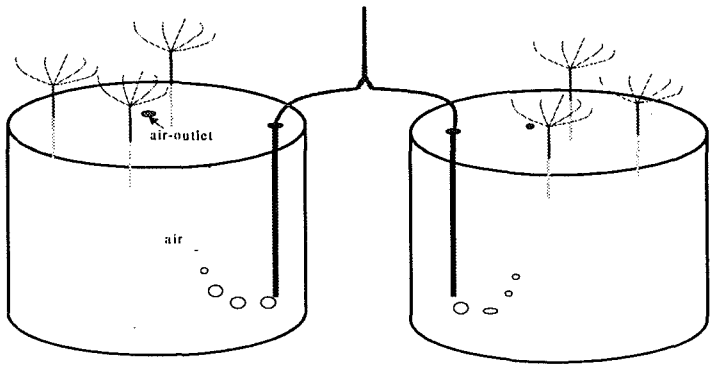


Figure 5.2. Planting of seedlings in PEG 4000 rooting medium of different water potentials

The seedlings were grown in pots for 7 days in a controlled environment cabinet as described in 5.3.1.2. The rooting medium was changed every second day (Appendix 5). There were three plants in each of three pots for each of the six water potentials. Seedlings were grown for 7 days. At harvest, the total root length and shoot length were measured, and root and shoot elongation rates were calculated as the average elongation rate during the experimental period.

5.3.3 Statistical Analysis

5.3.3.1 Experiment I

The variance of measured data of seedling growth might come from soil matric potential, soil strength and soil air-filled porosity. Among them soil strength treatment was the categorical factor, and therefore variance from soil strength treatment was analysed first. SAS GLM procedure was then used to test the variance of seedling growth with water potential, air-filled porosity and soil strength at the same target soil strength level and the regression formula between root elongation rate and soil water potential was established.

5.3.3.2 Experiment II

The variance in seedling growth might come from water potential treatments and pot treatments. SAS ANOVA procedure was used to analyse the variance source, and then SAS GLM and SAS NLIN procedures were used to establish linear and non-linear models to simulate the response of seedling growth to water potential.

5.4 Results

5.4.1 Soil Physical Property Variation at Harvesting in Experiment I

Controlling the humidity in the growth cabinet and using the taped ring technique were very effective in reducing the water loss from the experimental samples. The water loss by volume from planting to harvest (7 days) averaged over the whole tube ranged from only 0.0046 cm^3 cm^{-3} to the maximum of 0.0304 cm^3 cm^{-3} with an average of 0.016 cm^3 cm^{-3}, which accounted for an average of 4.69% decrease from the initial water content (Figure 5.3.a). Air-filled porosity gain by volume will be equivalent to water loss. The increase in air-filled porosity ranged from about 2% to about 14% with an average of 7.7% (Figure 5.3.b). Converting water variation data to soil strength and soil matric potential, it represented an average increase about 10% in soil strength and an average decrease of about 50% in soil matric potential from planting to harvest (averaged over the whole tube) respectively (Figure 5.3.c and d).

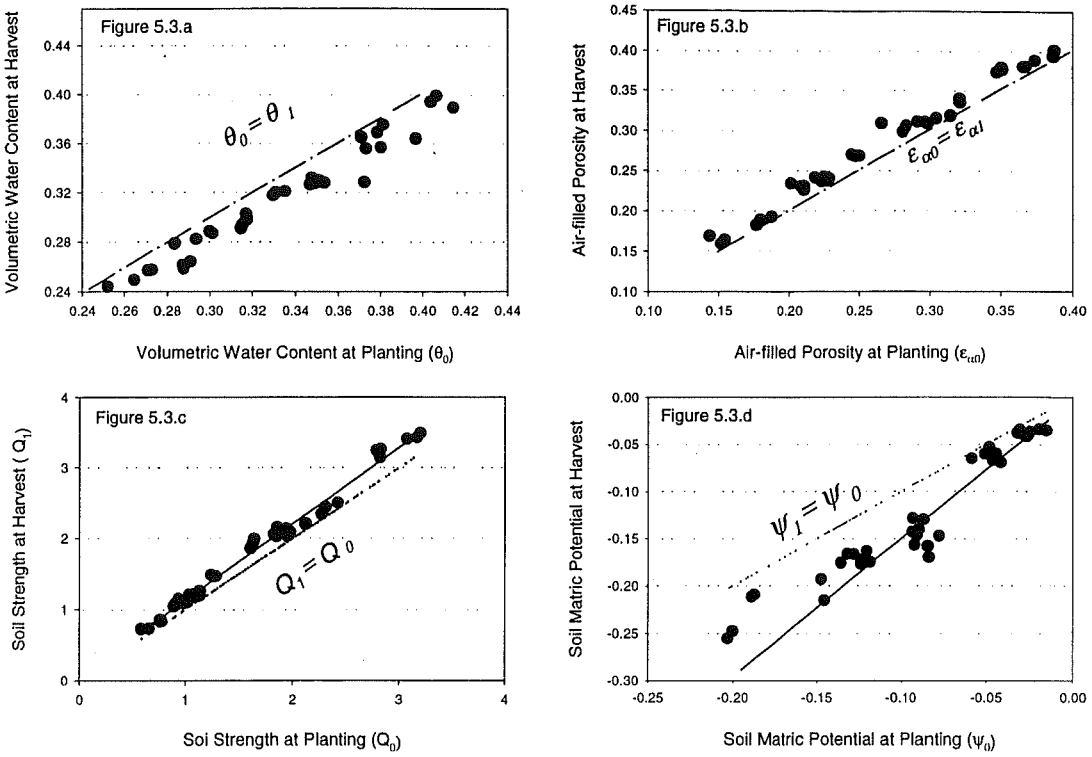


Figure 5.3. Changes of soil physical properties during the experimental period in the argillite soil samples. θ_0, ε_{a0}, Q_0 and Ψ_0 represent water content (cm^3 cm^{-3}), soil air-filled porosity (cm^3 cm^{-3}), soil strength (MPa) and soil matric potential (-MPa) at planting respectively. θ_1, ε_{a1}, Q_1 and Ψ_1 represent water content, soil air-filled porosity, soil strength and soil matric potential at harvest respectively.

During the period from planting to harvest the soil physical properties were observed to change with soil depth. The changes were mainly in the first 25 mm soil layer and almost no changes were detected deeper than 25 mm. Figure 5.4 demonstrates the changes of soil physical properties both temporally and spatially in an argillite soil:

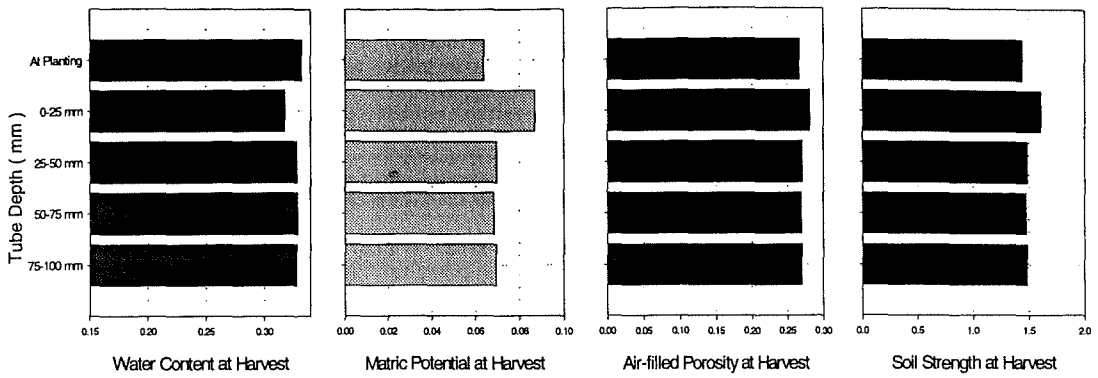


Figure 5.4. Changes of soil physical properties both temporally (at planting and at harvest) and spatially (distribution with depth at harvest) in the argillite soil sample (ρ_b= 1.0 g cm^{-3}). At planting, water content = 0.332 cm^3 cm^{-3}, water potential = -0.07 MPa, soil strength =1.44 MPa, air-filled porosity = 0.27 cm^3 cm^{-3}

In this study, the most appropriate values for soil strength and air-filled porosity were considered to be the initial values (at planting) but for matric potential the most appropriate values were considered to be the mean values over the period from planting to harvest. The justification for this is as follows:

The average elongation rate of root was about 6 mm day^{-1}. Therefore it took only four days for the root to penetrate through the top 25 mm of soil. This is also the soil depth over which almost all of the temporal variation in strength and air-filled porosity occurred. Over the whole planting to harvest period (7 days) the water loss was gradual and therefore the corresponding changes in soil strength and air-filled porosity were also gradual. The temporal variability in these factors would be overshadowed by the spatial variability of these factors in the soil at the time of planting (10% or less). It is therefore more accurate to use the initial values of soil strength and air-filled porosity in modelling root growth.

The largest variation over time was in the soil matric potential, with an average reduction of about 50% of the established initial soil matric potential. However it is

difficult to precisely monitor the water potential change with depth over the plant growing period, therefore the average of water potential between planting and harvesting was determined to approximately represent the water potential experienced by root penetration. By doing so, it actually increased the variation of water potential since the same water loss accounted for different matric potential change in different textures and in the same texture at different bulk densities (Chapter 4) and slightly increased the original water potential range (- 0.01 to - 0.2 MPa).

5.4.2 Seedling Growth in Soils

Analysis of variance of the root elongation rate (ΔR), shoot elongation rate (ΔS), total root biomass (R_m) and total shoot biomass (S_m) is summarised in Table 5.2. The root elongation rate and total root biomass were significantly related to soil strength treatment, but there was no significant relationship for the shoot elongation rate and total shoot biomass.

Table 5.2. p values from analysis of variance for the root elongation rate (ΔR), shoot elongation rate (ΔS), total root biomass (R_m) and total shoot biomass (S_m) against soil strength treatment (Q Treatment)

Variance Source	ΔR	ΔS	R_m	S_m
Q Treatment	<0.0001	0.331	<0.0001	0.602

The effect of the soil strength treatment was expected since the two target soil strength levels were significantly different. A further analysis was carried out at each soil strength level to establish the possible relationship between soil matric potential and root growth.

At each target soil strength level, the factors that directly determine seedling growth include soil matric potential and soil air-filled porosity. Although soil strength was designed as a constant value, in fact the soil strength value at each potential level was subject to minor variation (10% variation, Table 5.1) and the contribution of this variation to root growth rate should also be tested. Therefore soil air-filled porosity, soil matric potential and soil strength all were treated as continuous variables to test the variance using SAS GLM procedure and the results are given in Table 5.3:

Table 5.3. p values from analysis of variance for root elongation rate (ΔR), shoot elongation rate (ΔS), total root biomass (R_m) and total shoot biomass (S_m) from soil air-filled porosity (ε_a), soil matric potential (Ψ_m) and soil strength (Q)

Q levels	Variance Source	ΔR	ΔS	R_m	S_m
0.5 MPa Level	Ψ_m	***<0.0001***	***<0.0001***	0.971	0.079
	Q	0.305	*0.046*	0.935	0.591
	ε_a	0.954	0.287	*0.05*	*0.052*
1.5 MPa Level	Ψ_m	***<0.0001***	***<0.0001***	0.052	*0.043*
	Q	0.516	*0.013*	0.377	0.246
	ε_a	*0.13*	0.236	0.196	0.201

For both target levels of soil strength, root elongation rate and shoot elongation rate were very highly significantly ($p < 0.0001$) related to soil matric potential. Shoot elongation rate was significantly ($p < 0.05$) related to soil strength for both target levels of soil strength and shoot biomass was significantly ($p<0.05$) related to to matric potential for the 1.5MPa soil strength target level. Otherwise all effects were not significant at $p<0.05$. Therefore, as far as root elongation rate is concerned, the objective has been achieved in isolating the effects of matric potential from those of soil strength and air-filled porosity.

The root elongation rates at two soil strength levels are plotted against soil matric potential in Figure 5.5:

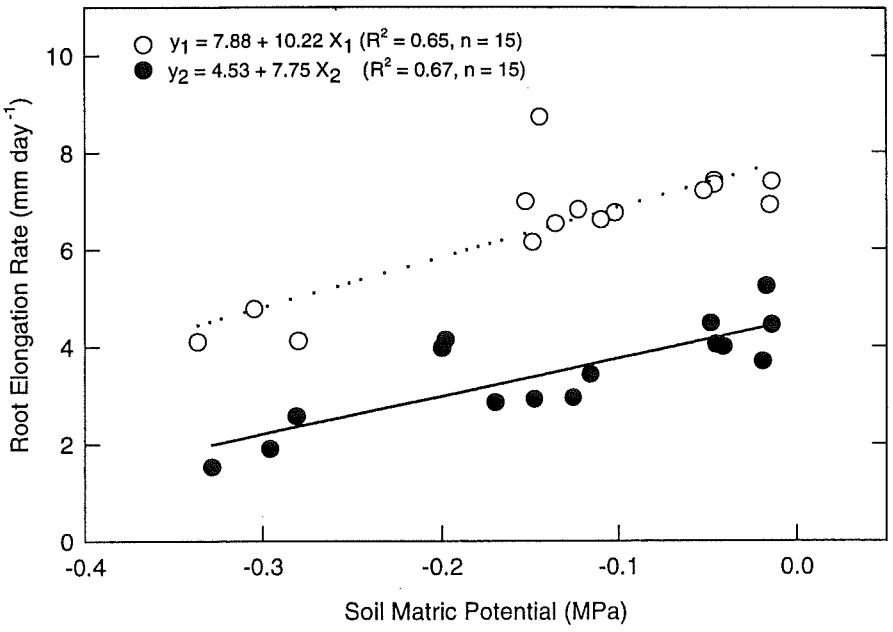


Figure 5.5. Root elongation rate against soil matric potential at two soil strength target levels (STD is the standard deviation)

Root elongation rates decreased with the decrease of soil matric potential at both soil strength target levels. Statistical analysis using SigmaPlot 4.0 showed that root growth rate was significantly related to soil matric potential ($p < 0.001$) at 0.5 and 1.5 MPa target soil strength levels and this relationship can be represented by linear regression model (5.1):

$$\Delta R = \alpha + \beta \Psi_m \qquad (5.1)$$

where ΔR = root elongation rate (mm day $^{-1}$), -0.01 MPa > Ψ_m > -0.34 MPa, α is the intercept and β the slope of the linear regression as listed in Table 5.4:

Table 5.4. Parameter test for the linear regression model between soil matric potential and root growth rate at two soil strength levels. Q = soil strength (MPa), Ψ_m = soil matric potential (- MPa), STD = standard deviation, DF = degree of freedom, p = significance level

Q (MPa)	Model	Parameter	Estimate	STD	DF	p
0.47 ± 0.08*	R^2 =0.665	α	7.89	0.33	14	<0.0001
	p< 0.0001	β	10.22	2.01	14	<0.0001
1.58 ±0.14**	R^2=0.671	α	4.54	0.26	14	<0.0001
	p =0.0002	β	7.75	1.51	14	<0.0002

*0.5 MPa target soil strength level; ** 1.5 MPa target soil strength level

Root elongation rate decreased with the decrease of soil matric potential. At the low target soil strength level, the slope of the regression line was larger than that at the higher target soil strength level (Table 5.4). This suggests that a given change in soil matric potential has a greater effect in a loose soil than in a compacted soil. The intercept (α) at the target strength of 1.5MPa was smaller than at 0.5MPa. This indicated higher soil strength had a significantly greater detrimental effect on the root elongation rate.

This linear regression exists when soil matric potential was as low as -0.30MPa. However the use of this linear regression in this study will be restricted to a soil water potential range between -0.01 and -0.20 MPa which has been defined arbitarily as a high water potential range.

5.4.3 Root Growth in Solution Rooting Medium

Analysis of variance indicated that the effect of water potential of the rooting medium on both root growth rate and shoot growth rate was very highly significant ($p < 0.0001$). When the osmotic potential of the solution decreased, root elongation rate also decreased (Figure 5.6).

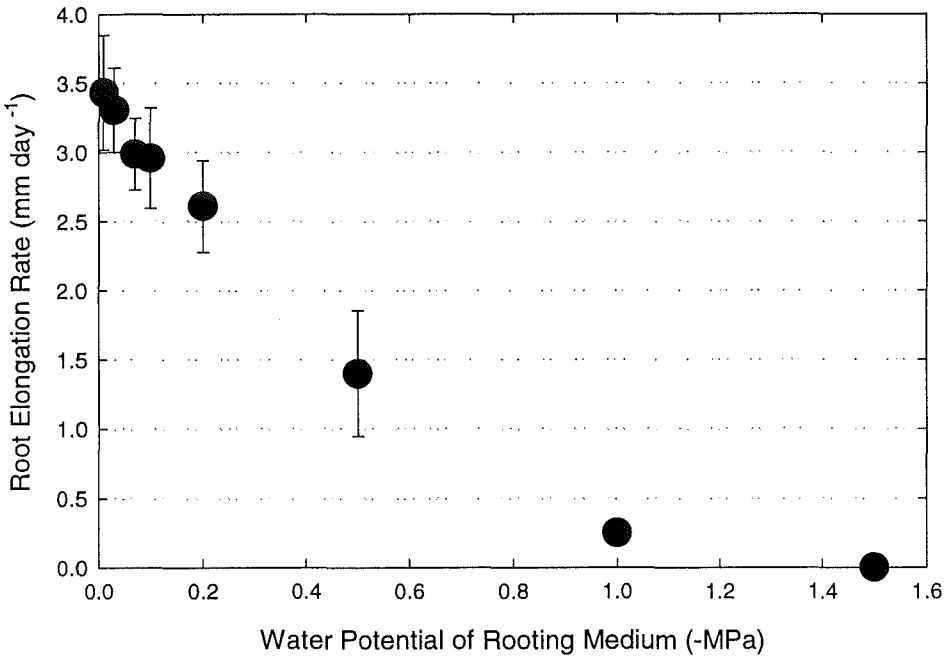


Figure 5.6. Relationship between root elongation rate and water potential (-0.01 to -1.5 MPa) in PEG 4000 rooting medium (error bar is standard deviation)

When the osmotic potential in the solution rooting medium was relatively high (-0.01 to -0.2 MPa), root elongation rate decreased linearly with the decrease of water potential (Figure 5.7):

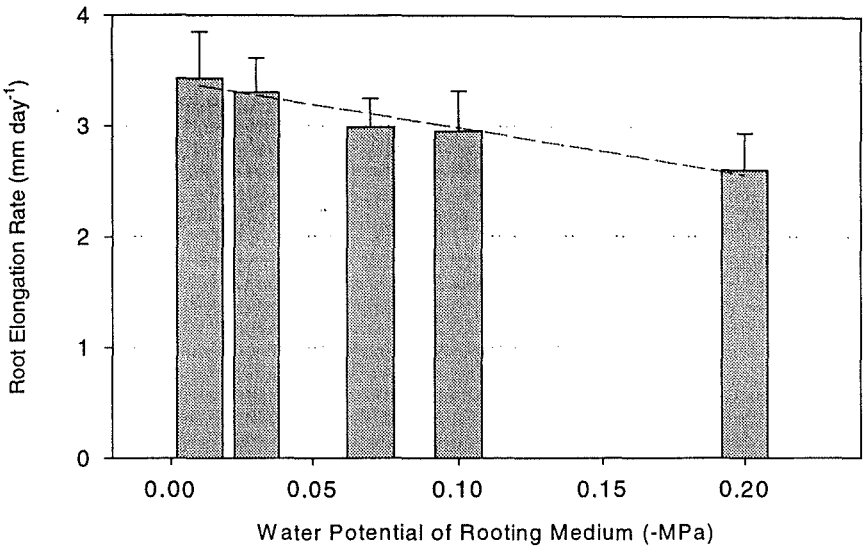


Figure 5.7. Relationship between root elongation rate and water potential (-0.01 to -0.2 MPa) in PEG 4000 rooting medium (error bar is standard deviation)

This relationship was established using the SAS GLM procedure:

$$\Delta R = \alpha + \beta \Psi \tag{5.2}$$

where ΔR = root elongation rate, Ψ = water potential of solution rooting medium (> - 0.20 MPa), $\alpha = 3.78 \pm 0.236$, $\beta = -7.29 \pm 2.22$ ($R^2 = 0.45$, $p < 0.0001$, $n = 15$)

Because water potential in solution rooting medium was designed as a categorical factor, when it was treated as a numerical variable, the variance of individual seedlings within the potential level contributed largely to the variance and decreased the R^2 and increased the standard error of the parameters.

When the osmotic potential in solution was lower than -0.20 MPa, the decreasing rate of root elongation slowed down (Figure 5.7). Seedlings grown in -1.5 MPa osmotic

potential withered in a couple of hours and both the root growth rate and shoot growth rate were zero.

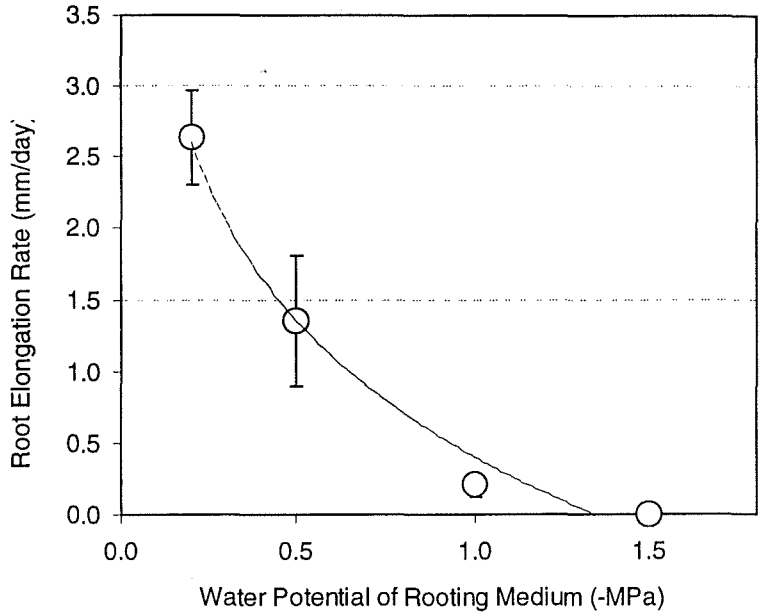


Figure 5.8. Relationship between root elongation rate and water potential (-0.20 to -1.5 MPa) in PEG 4000 rooting medium (error bar is standard deviation)

The relationship between root elongation rate and osmotic potential was fitted by a logarithmic model (SAS NLIN Procedure) as 5.3:

$$\Delta R = \alpha + \beta \ln |\Psi| \qquad (5.3)$$

where ΔR = root elongation rate , Ψ = water potential (-MPa) ($-1.5 < \Psi \leq -0.20$ MPa), $\beta = -1.31 \pm 0.20$, $\alpha = 0.49 \pm 0.188$ (RMS = 1.30, $p < 0.001$, $n = 48$)

Using model 5.3, the root of radiata pine was calculated to stop growing at a water potential of - 1.45 MPa, and this point can be explained as the extreme soil water potential in which a radiata pine root can function.

The response of shoot growth was different from root growth. The relationship between shoot growth rate and the water potential of rooting medium is represented in Figure 5.9.

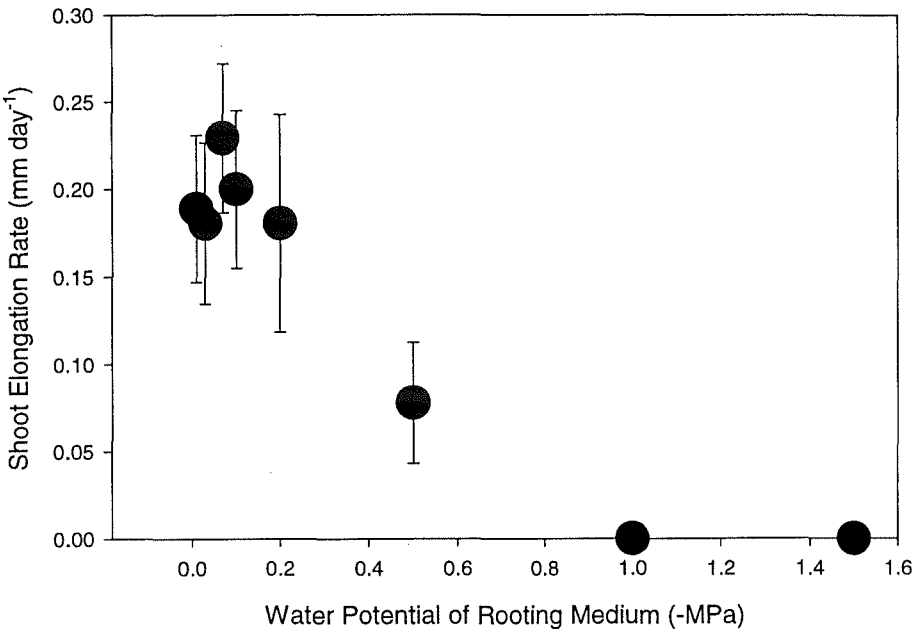


Figure 5.9. Relationship between shoot growth rate and water potential of the rooting medium (error bars are standard deviation).

There was no significant decrease of shoot growth rate when the water potential of rooting medium was higher than -0.20 MPa (p =0.92), with an average shoot elongation rate of only 0.198 mm day $^{-1}$. Significant shoot growth rate decrease was observed when the water potential of the rooting medium dropped to -0.50 MPa. The shoot growth ceased at -1.0 MPa water potential which was higher than the water potential at which root elongation ceased (-1.45 MPa). Sharp *et al.* (1988) observed that the primary root of maize (Zea mays L.) grown in vermiculite continued slow rates of elongation at water potentials which completely inhibited shoot growth.

5.5 Discussion

The root growth model in soil given by Yau & Sands (1992) is:

$$\Delta R = \Phi (\Psi_m - \Psi_\pi - Y - P_s) \quad (5.4)$$

where ΔR = root elongation rate, Ψ_m = soil matric potential, Ψ_π = root cell osmotic potential, Y = yield turgor, P_s = mechanical impedance, Φ = wall yielding coefficient

$$\Delta R = b + \Phi\Psi_m \quad (5.5)$$

where $b = -\Phi (\Psi_\pi + Y + P_s)$

In this experiment, soil strength was constant, and therefore P_s was constant. Greacen and Oh (1972) suggested that there was no osmoregulation when soil water potential was higher than -0.28 MPa in which case Ψ_π would also be constant. If Y and Φ are also constant at high water potential (-0.01 to -0.20 MPa), then Equation 5.5 indicates that root growth rate decreases linearly with the decrease of soil matric potential at a given soil strength with a slope of Φ. The highest root elongation rate is b which is mainly determined by soil mechanical impedance (soil strength) since root osmotic potential and yield turgor are assumed relatively constant. The maximum rate of root elongation at soil strength of 0.50 MPa is 7.89 mm day^{-1} compared with 4.54 mm day^{-1} at 1.5 MPa soil strength (Table 5.4). Establishment of this linear regression equation indicates that in the higher water potential range (-0.01 to – 0.2 MPa) the effect of water potential on cell elongation was based on a physical pressure adjustment process.

The effect of soil water potential on root growth depends on soil strength. The slope of the linear regression line declined from 10.22 mm day^{-1} MPa^{-1} at low soil strength (0.50 MPa target soil strength level) to 7.75 mm day^{-1} MPa^{-1} at high soil strength (1.50 MPa target soil strength level) (Table 5.4). This indicated that a change in soil water

potential has a much greater effect in a loose than in a compacted soil. One possible explanation to this is that the change of soil water potential might be less efficient in increasing the turgor pressure of root tissue in high soil strength. Another explanation is that the root growth in high soil strength may be seriously restricted by soil strength and the influence of soil water potential becomes minor.

Based on these assumptions, the change of water potential in solution without soil strength should have the largest effect on root elongation rate. However, the slope of the linear regression line in PEG 4000 rooting medium was 7.29 mm day $^{-1}$ (Equation 5.2) which is lower than that in 0.5 MPa soil strength level and is numerically close to that in 1.50 MPa soil strength level (Table 5.4). The maximum root elongation rate was 3.78 mm day $^{-1}$ that is significantly lower than in soil treatment. One possible reason is that the root elongation rate in rooting medium was determined as the root growth of established seedlings instead of from radicle of pregerminated seeds as in the soil experiment. Some factors besides water potential and soil strength might have contributed to the root growth and the absolute values from both soil experiment and rooting medium experiment are not directly comparable. There is some evidence to suggest that PEG in the rooting medium can suppress root function. Lesham (1966) and Lawlor (1970) showed that PEG could be toxic to plant roots and Mexal *et al.* (1975) showed that the oxygen diffusion rate to roots is restricted in PEG 4000 solutions. This could explain the lower values of root elongation rate recorded in the PEG4000 media than in soil at the same water potential.

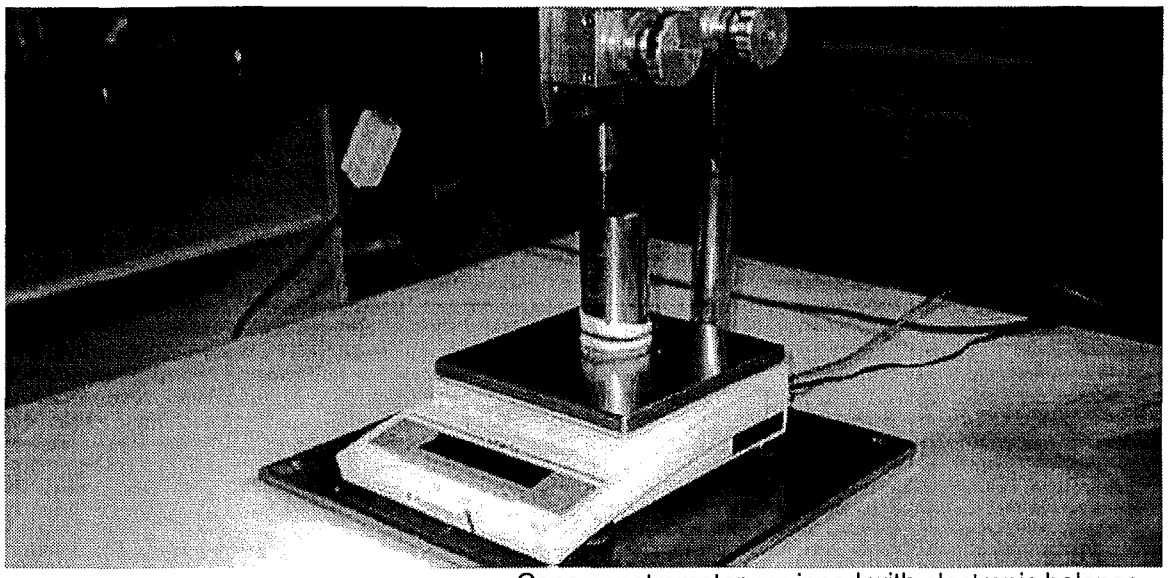
Results from the solution experiment showed that when water potential was lower than -0.2 MPa, with the continuous decrease of water potential, the decreasing rate of root elongation rate slowed down. The elongation rate was linearly related to the log of the absolute value of water potential as shown in Figure 5.8. Because there was no water treatment between -0.2 and -0.50 MPa, the precise determination of the water potential where this change commenced is very difficult. Therefore -0.20 MPa was used as an arbitrary value for convenience and further discussion. This suggests some physiological processes were induced when water potential was lower than -0.20 MPa.

These physiological processes might include changes of any one of osmotic potential, yield turgor and wall yielding coefficient or all of them. Further discussion will be given in Chapter 7.

In order to exclude the possible effect from soil air-filled porosity, the air-filled porosity in all soil samples was established higher than 0.10 cm^3 cm^{-3}, which was conventionally thought to be ideal for root growth. However very recent results from Penfold (1998) indicated that the ideal air-filled porosity for radiata pine growth in the repacked soils could be as high as 0.16 cm^3 cm^{-3}. Fortunately all treatments except for one (argillite, bulk density = 1.1 g cm^{-3} at water potential of -0.01 MPa, air-filled porosity 0.144 cm^3 cm^{-3}) had an air-filled porosity greater than 0.16 cm^3 cm^{-3}. The statistical analysis didn't detect any significant effect from soil air, and this also supports the argument that these experiments were not affected by air-filled porosities.

CHAPTER 6

INFLUENCE OF SOIL STRENGTH ON ROOT GROWTH OF PINUS RADIATA SEEDLINGS



Cone penetrometer equipped with electronic balance

6.1 Abstract

The influence of soil strength on seedling growth of radiata pine was studied using loamy sand soil (pumice) repacked to a range of soil bulk densities. The root elongation rate decreased exponentially with increase of soil strength at a given soil matric potential when soil aeration was not limiting. The diameter of both root and root tip increased with soil strength. However the shoot elongation rate and diameter were

independent of soil strength. Root biomass reduced with increase of soil strength and no significant relationship between shoot biomass and soil strength was observed.

Experiments using soils of different textures gave similar results and indicated that these relationships were independent of soil textures.

Key Words: *Pinus radiata* D. Don; soil compaction; soil strength; mechanical impedance; root elongation rate

6.2 Introduction

Soil compaction can reduce the productivity of radiata pine (*Pinus Radiata* D. Don) (Sands and Bowen, 1978; Greacen and Sands, 1980; Gayoso and Schlatter, 1982; Murphy *et al.*, 1997). Soil compaction increases soil strength, decreases soil air-filled porosity and changes the soil water-holding characteristic. Both increased soil strength and decreased soil air-filled porosity influence site productivity by confinement or constraint of the development of root system.

At the present time, there is not an effective method to directly measure the soil mechanical impedance experienced by roots. A widely used method is to measure the penetrometer soil strength to represent mechanical impedance (Warkotsch, 1994) and penetrometer soil strength is well correlated with root penetration (Barley and Greacen, 1967; Bengough, 1991; Costantini *et al.*, 1996b).

In this experiment, pre-germinated seeds of radiata pine were planted into soil samples of different degrees of compaction at constant soil matric potential while maintaining an ideal soil air-filled porosity to test the quantitative relationship between seedling growth and soil strength. This relationship was then tested in soil of different textures.

6.3 Materials and Methods

Pumice soil was uniformly repacked into 100 mm long × 48 mm inner diameter stainless steel tubes to 6 bulk density levels (0.70, 0.75, 0.775, 0.80, 0.825 and 0.85 g cm^{-3}) using the packing techniques described by Misra and Li (1996). There were at least 6 tube replicates (up to 8 replicates) for each bulk density. All these soil samples were saturated in a water bath overnight and then equilibrated in a pressure chamber at – 0.01 MPa soil matric potential. All the four soil textures described in Chapter 3 were repacked into the same type of stainless steel tubes to three bulk density levels (low, medium and high) as described in 4.3.1. Repacked soil samples were equilibrated at -0.1 MPa soil matric potential. Soil volumetric water content was determined immediately after the soil samples achieved equilibrium and soil air-filled porosity was calculated by methods described in 4.2.3.

Soil strength was measured by a custom-designed laboratory cone penetrometer as described in 4.2.3. The means of soil strength values measured between the penetration depth from 10 – 12.5 mm were recorded as the sample soil strength (see 6.5.1).

Three pre-germinated radiata pine seedlings with about 2 mm long radicles were planted in each tube (refer 5.2.5 for pre-germinating and planting methods in detail). For each sample tube, a steel ring of 15 mm height was packed to the same bulk density using the same soil and was taped above the sample tube to reduce direct water evaporation and to prevent the seedling from lifting when the root encountered high soil strength. Both the bottom of the tube and the connecting area of ring to tube were sealed with airtight plastic. The seedlings were grown in a controlled environment cabinet (light period: 20 ^{0}C, 12 hours, 80% relative humidity, 700 μm m^{-2} s^{-1} photosynthetically active radiation; dark period: 17 ^{0}C, 12 hours, 80% relative humidity) for seven days.

At harvest, seedlings were removed from the soil samples and cleaned, and the seedling length, root length and shoot length were directly measured. Root and shoot elongation rates were calculated as the average growth rate of the three seedlings in the same tube during the growing period. Root and shoot diameters were measured by calliper and in the middle point of the shoot and root segments and the root tip diameter was measured under a microscope using measuring eyepieces. After these measurements, roots and shoots were separated at the root collar and oven-dried at 70^0C for 72 hours to determine biomass.

6.4 Results

6.4.1 Root Elongation Rate and Soil Strength at Constant Matric Potential

No significant effects from the tube replicates were detected ($p < 0.05$). Almost all the variance came from the bulk density treatments ($p<0.0001$).

The effect of bulk density treatment was the combined result of soil matric potential, soil air-filled porosity and soil strength. However, the soil matric potential was constant in all the bulk density treatments and the air-filled porosity for all bulk density treatment was higher than 0.32 cm^3 cm^{-3}, far higher than the limiting air-filled porosity of 0.16 cm^3 cm^{-3} for radiata pine growth in repacked soil (Penfold, 1998). Therefore the variance of root elongation rate was a sole effect from soil strength. Because there was no effect from the tube replicates, each tube replicates was then treated equally as a single observation instead of using means to increase the degrees of freedom. The relationship between root elongation rate and soil strength is presented in Figure 6.1:

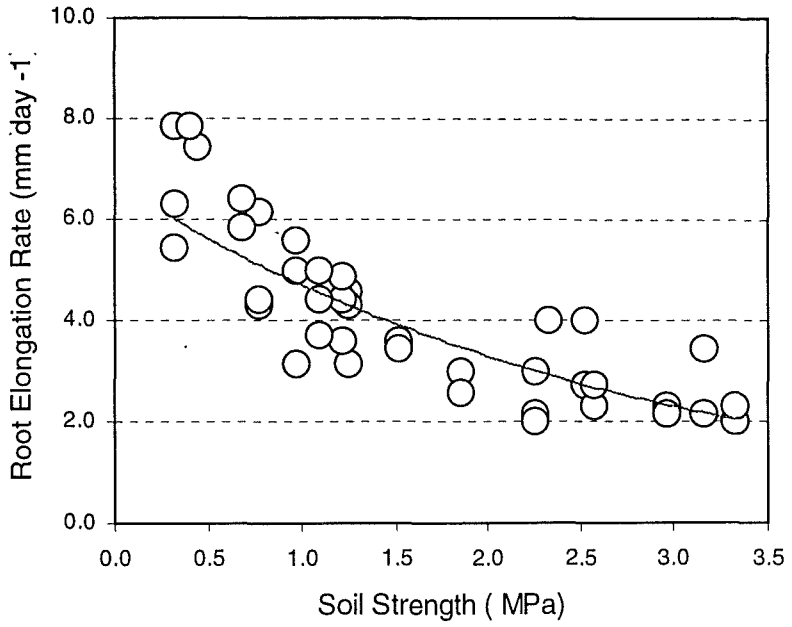


Figure 6.1. Relationship between root elongation rate and soil strength at constant soil matric potential (-0.01 MPa) in pumice soil

The relationship between root elongation and soil strength (Figure 6.1) is non-linear and therefore non-linear regression analysis was carried out using SAS NLIN procedure. The relationship is best described by the exponential formula:

$$\Delta R = \alpha e^{-\beta Q} \qquad (6.1)$$

where ΔR = root elongation rate (mm day $^{-1}$), Q = soil strength (MPa), $\alpha = 8.29 \pm 0.49$, $\beta = 0.49 \pm 0.042$, and RMS (residual mean square) = 0.886.

Root elongation rate decreased exponentially with the increase of soil strength. Root elongation rate decreased mainly over the low strength range, and decreased to half of its maximum elongation rate at about 1.4 MPa.

6.4.2 Relationship between Shoot Elongation Rate and Soil Strength

Response of shoot growth to increased soil strength was totally different from root growth. No significant difference of shoot growth rate was detected across the experimental range of soil strength as shown described in Figure 6.2:

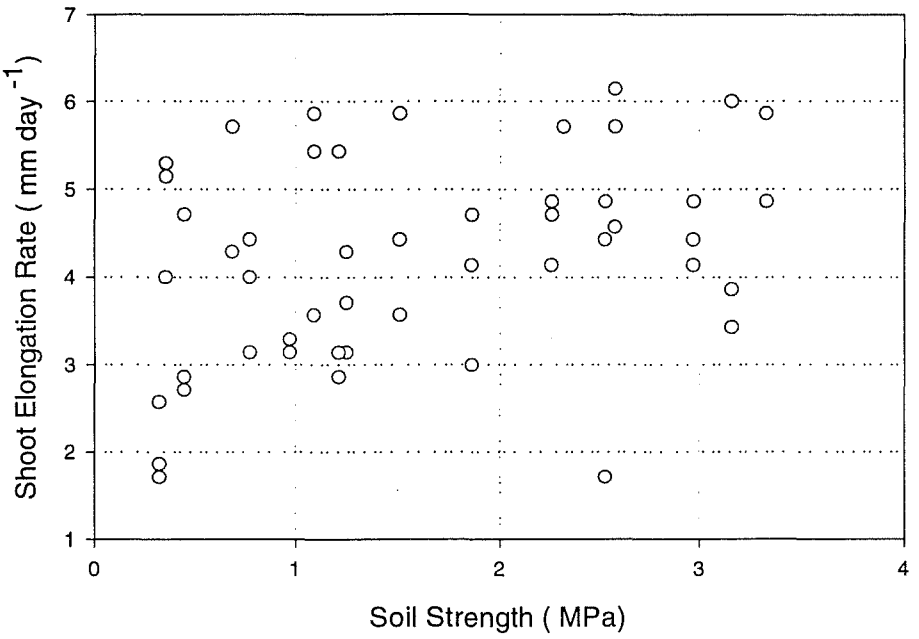


Figure 6.2. Relationship between shoot growth rate and soil strength at constant soil matric potential (-0.01 MPa) in pumice soil

6.4.3 Changes of Root and Shoot Diameters, Total Root and Shoot Biomass with Soil Strength

When the root elongation process was restricted by higher soil strength, this induced a series of morphological and physiological process to happen (Figure 6.3).

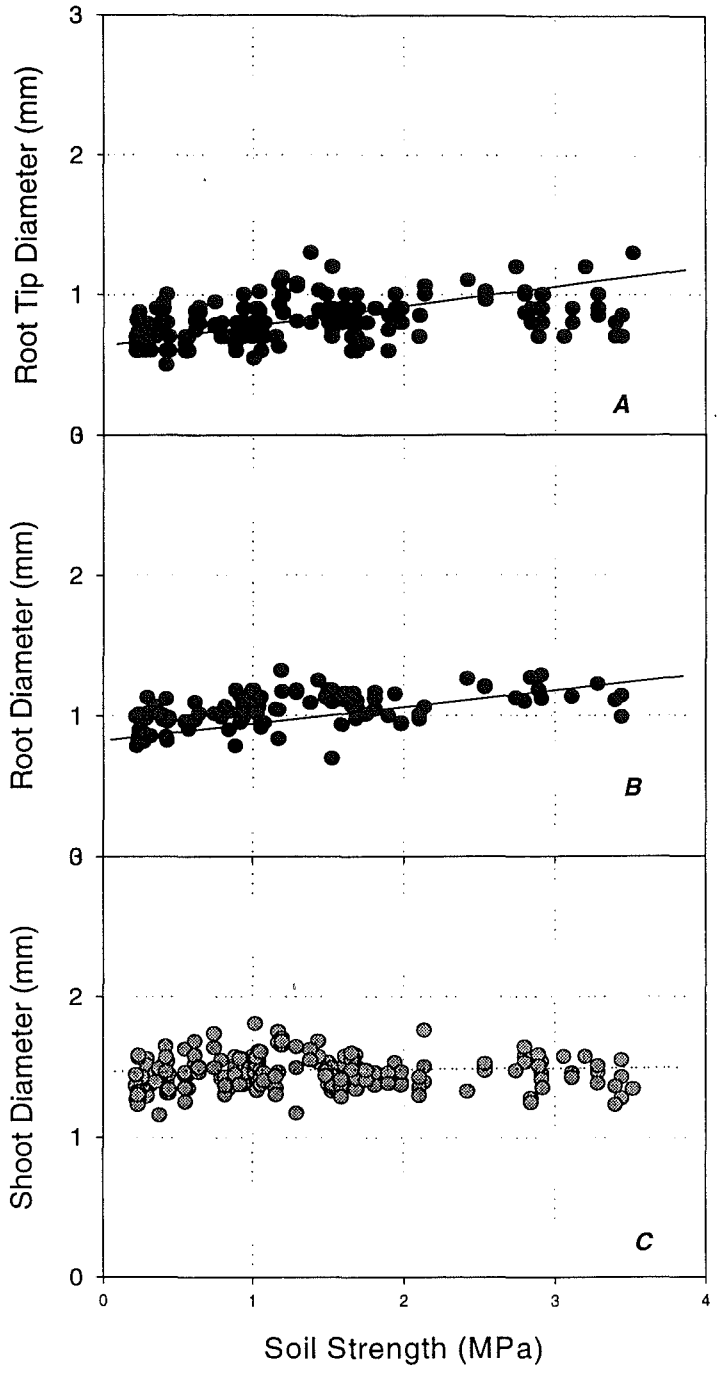


Figure 6.3. Changes of root, root tip and shoot diameters of radiata pine seedlings with increased soil strength

Both the diameter of the root at the tip (Figure 6.3A) and in the middle point of the root segment (Figure 6.3B) increased with soil strength, but no diameter increase in the shoot was observed (Figure 6.3 C).

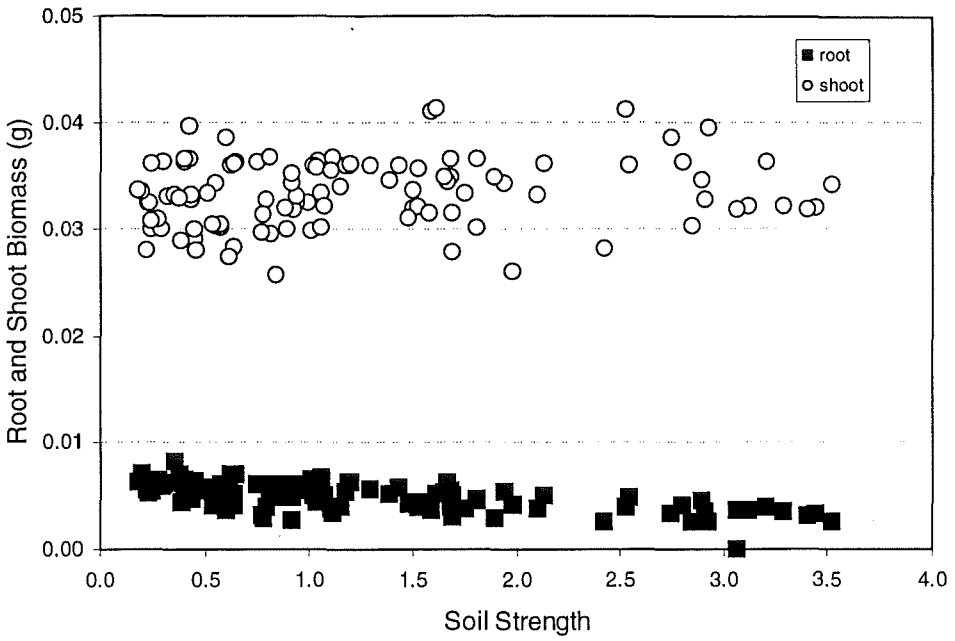


Figure 6.4. Responses of root and shoot biomass to increased soil strength

With increase of soil strength, no obvious variation of shoot biomass was observed and root biomass decreased with increase in soil strength (Figure 6.4).

6.4.4 Relationship between Root Elongation Rate and Soil Strength in Contrasting Soil Textures

The relationship between root elongation rate and soil strength was then tested in soils of different textures at matric potential of -0.10 MPa while maintaining ideal air-filled porosity (> 0.19 cm^3 cm^{-3}) and is shown in Figure 6.5:

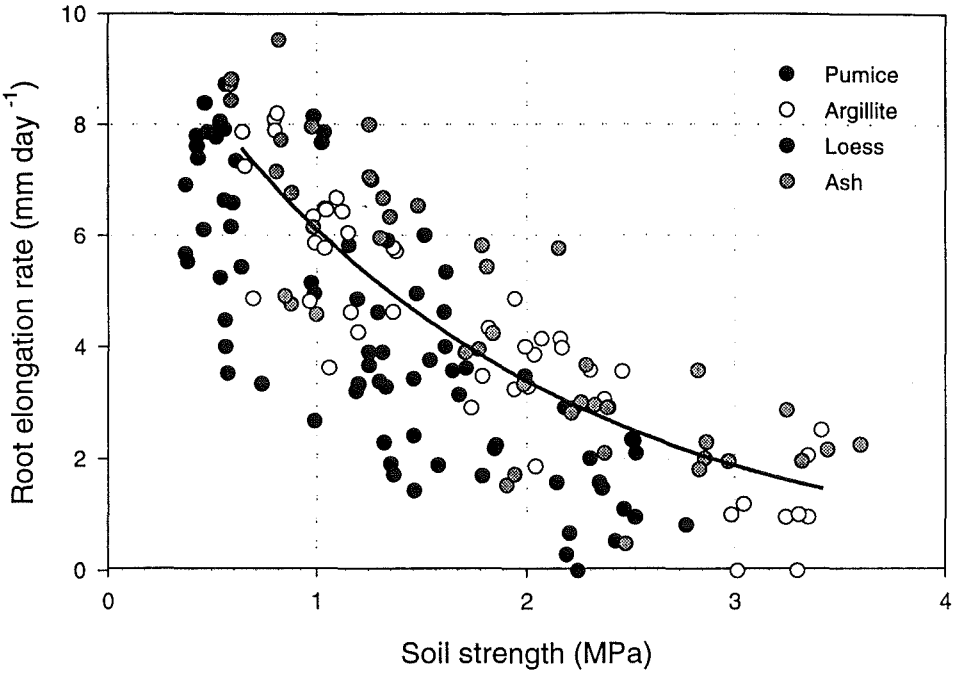


Figure 6.5. Response of root elongation rate to soil strength in soils of contrasting textures (Soil matric potential = - 0.10 MPa, air-filled porosity > 0.20 cm^3 cm^{-3})

SAS GLM procedure was used to test the variance of the log value of root elongation rate (LNΔR) with the soil texture treatment and the soil bulk density treatment. There were no significant effects from soil texture ($p = 0.055$) and the interaction of soil texture and bulk density treatment ($p = 0.47$). The log value of root elongation rate was significantly related to bulk density treatment ($p < 0.0001$).

6.5 Discussion

6.5.1 Determination of Soil Strength

When the metal probe of the penetrometer was pushed into soil sample, the measured soil strength increased with the penetration depth (Figure 6.6).

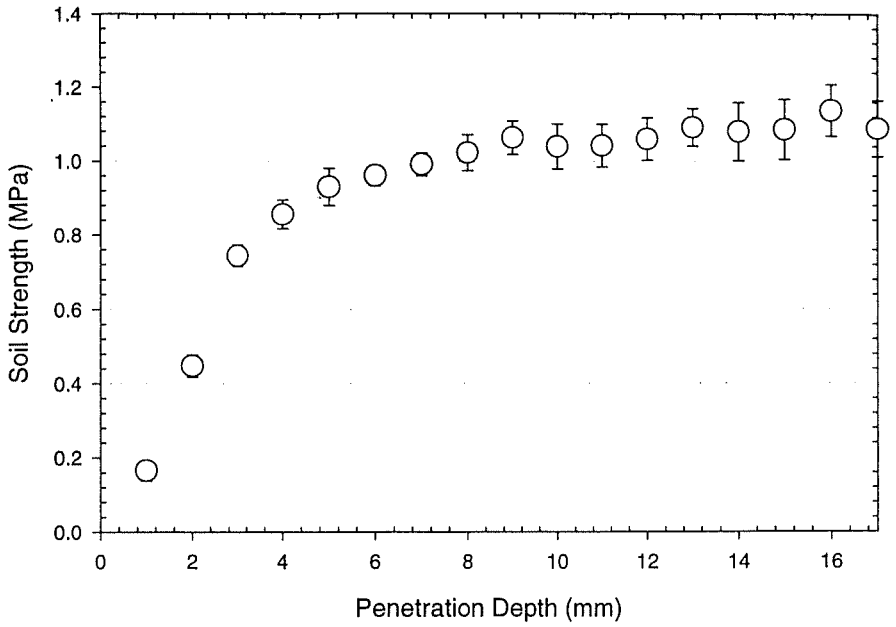


Figure 6.6. Relationship between soil strength and penetration depth (Cone angle = 60 degree, cone base diameter = 2mm. Pumice soil, ρ_b = 0.80 g.cm^{-3}, error bar = S.E, n = 9)

During the first 3 mm, soil strength increased sharply. This is due to the gradual increase of the cone section area immersed into the soil sample. From 4 to 9 mm, the rate of increase in soil strength slowed down and after 10 mm the strength was relatively stable although a gradual increasing trend was still noticeable. The gradual increase of measured soil strength deeper than 10 mm can be explained as the results of: 1) the increased friction due to formation of a thin soil coat on the cone surface; 2) the possible bending of the metal probe; and 3) the effect of overburden. Therefore, the penetration depth for soil strength determination should be pre-defined according to probe diameter to best describe the actual soil strength condition. For the probe used in this experiment, the ideal penetration depth was around 10 mm, which is about 5 times the cone base diameter (Misra and Li, 1996). All the soil strength values used in this experiment were the means of 5 point strength values between 10 and 12.5 mm.

6.5.2 Vertical and Horizontal Soil Strength Distribution in Soil Samples

Figure 6.7 gives the actually measured soil strength distribution in repacked pumice soil samples at three bulk densities (0.7, 0.8, and 0.85 g cm^{-3}) at a soil matric potential of -0.20 MPa, using the packing techniques introduced by Misra and Li (1996). Soil strength was measured by a metal probe with a 30^0 semi-angle and a cone base diameter of 2.5 mm and total length of 100 mm. Position 1, Position 2 and Position 3 represent the three positions for planting seeds as described in 5.3.1.

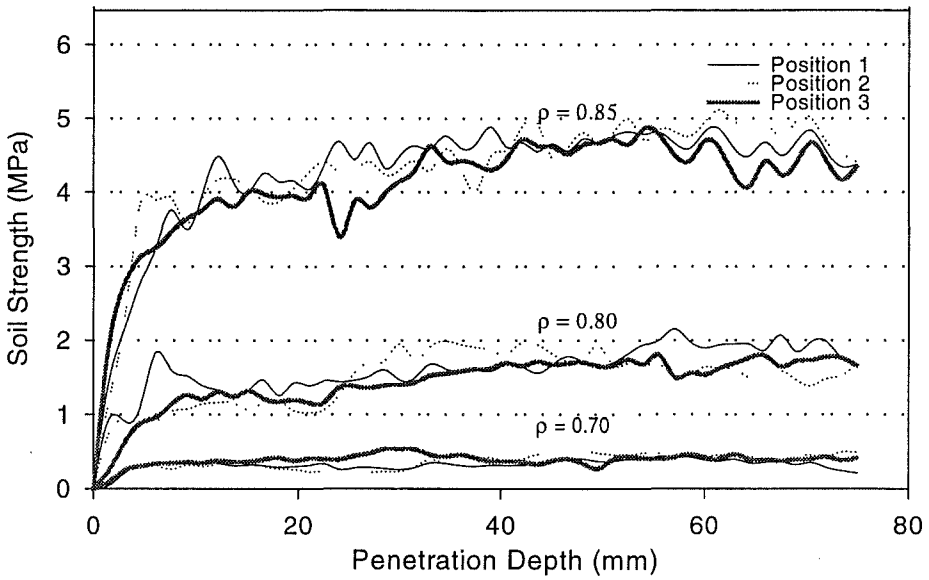


Figure 6.7. Horizontal and vertical distribution of soil strength in repacked pumice soil samples at three bulk density levels (ρ_b, g cm^{-3})

At the three bulk densities, when penetration was deeper than 15 mm (about 5 times the diameter of cone probe as described in Misra and Li, 1996), soil strength was relatively constant at low bulk density. This indicated that a uniform soil strength distribution with depth was achieved. A slight increase of soil strength with the penetration depth was observed in higher bulk densities. This probably was not due to packing method, but to the reasons explained in 6.5.1.

Soil strength distribution horizontally is also important since three seedlings were planted in one tube. Positions 1, 2 and 3 represent soil strength taken at the three positions as described in 5.3.1.2. The soil strength values measured at the three positions at a given soil bulk density were reasonably close (Figure 6.7).

6.5.3 Change of Soil Physical Properties at Harvest

Soil matric potential, soil air-filled porosity and soil strength were subject to change because of water loss from both seedling transpiration and evaporation of water from the soil surface. Because the seedlings were very small and were harvested before the needles were fully opened, water loss from seedling transpiration was very small. Water loss was almost totally from surface evaporation from the soil. Control of humidity and using soil in a ring taped above the sample effectively reduced the water loss. The most appropriate values for quoting soil strength and air-filled porosity were considered to be the initial (at planting) values (5.4.1). In contrast, matric potential might have changed during the experimental period (5.4.1). However, in each case all the samples had the same initial matric potential and were subject to approximately the same matric potential change over the short experimental period. Therefore the initial value for matric potential has also been used as the most appropriate value for quoting matric potential of the samples.

6.5.4 Shoot Growth and Soil Strength

Compared with root growth, shoot growth was less related to soil strength (Figure 6.2). Shoots need both water and nutrients for proper physiological function, and shoot growth would be restricted if root growth were seriously reduced. However, in this experiment, seedlings were only one week old and the root was in the radicle period. The nutrients for shoot growth might still largely rely on endosperm instead of from root absorption; meanwhile the relatively high water potential treatments make the root length less relevant to the water supplies to the shoot.

6.5.5 Mechanical Impedance and Soil Strength

In order to elongate in soil, a root has to penetrate through the soil matrix. In other words, soil offers a certain resistance to root penetration, which is called soil mechanical impedance to the root and is normally represented by P_s. It is difficult to measure P_s directly. It is generally believed that the soil strength value is larger than the mechanical impedance. The direct evidence is that the measured maximum pressure roots can generate is far smaller than the penetrometer strength of soil which roots can penetrate (Dexter, 1987; Bengough and Mullins, 1991), and the quantitative relationship between soil mechanical impedance and soil strength remains basically unknown.

Yau and Sands (1992) gave a model for root elongation in soil (see equation 5.5). In this experiment the matric potential of the soil was as high as could be sustained (–0.01 MPa) and therefore the value for $\Psi_m - \Psi_\pi - Y$ represents the maximum root growth pressure σ_{max} . Combining with equation 6.1:

$$\Phi(\sigma_{max} - P_s) = \alpha e^{-\beta Q} \tag{6.2}$$

$$\text{and } P_s = \sigma_{max} - (\alpha/\Phi)\, e^{-\beta Q} \tag{6.3}$$

At a constant value of σ_{max}, the root elongation rate at zero soil strength (ie Q = 0 MPa) is equal to both α and $\phi\sigma_{max}$ (equation 6.2). There is no direct determination of maximum root growth pressure for radiata pine, but most research about the root indicated that the maximum root growth pressure is around 1.0 MPa (Gill and Bolt, 1955; Dexter, 1987). Assuming the maximum root growth pressure σ_{max} in radiata pine is also around 1.0 MPa and Φ does not change with soil strength or only changes slightly with soil strength, then $\alpha \approx \Phi$. Equation 6.3 can be rewritten as:

$$P_s \approx 1 - e^{-\beta Q} \tag{6.4}$$

The quantitative relationship between soil strength and mechanical impedance can be calculated using Equation 6.4 and these results are shown in Figure 6.8:

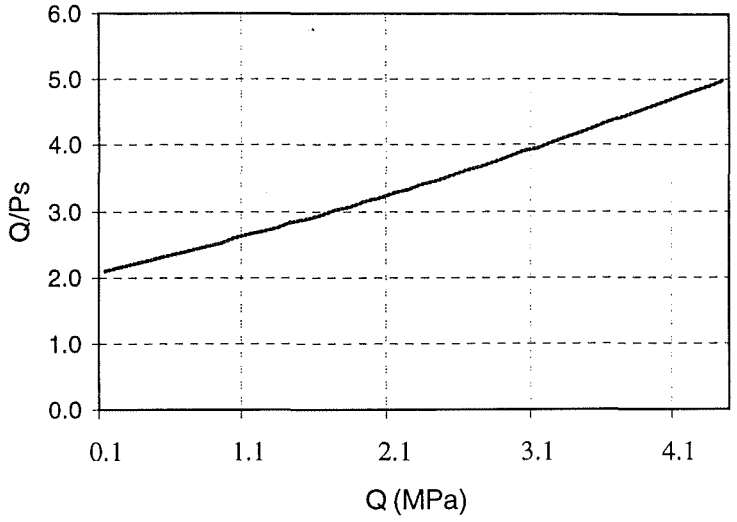


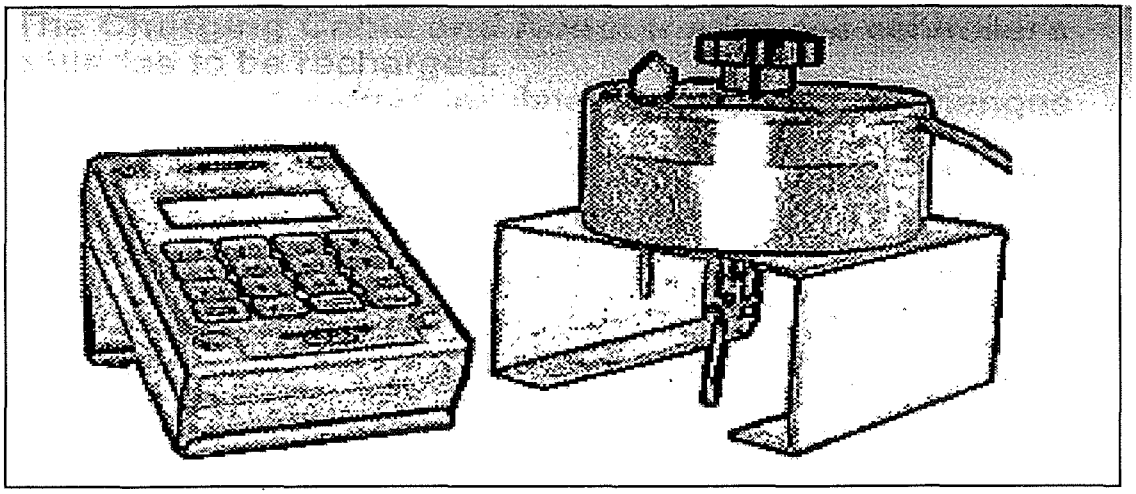
Figure 6.8. Relationship between soil mechanical impedance and penetrometer soil strength in pumice soil at -0.01 MPa soil matric potential

This suggests that when the soil strength is very low, the penetrometer soil strength is about two times the mechanical impedance, and the ratio increases progressively with increasing soil strength and is nearly four times when soil strength is around 3 MPa. This ratio is comparable with the reported 3 times in weak soil (Q = 0.5 MPa) by Dexter (1987) and 4.5-7.5 times recorded by Bengough and Mullins (1991) using a 30^0 semiangle, 1 mm diameter penetrometer. This shows that, relative to a penetrometer probe, a root is more efficient at penetration at higher soil strengths. This could be due to a more advantageous distribution of the stress applied to the soil such as would be expected from an increase in the diameter of the root tip (Figure 6.3). Materechera *et al.* (1991), Constantini *et al.* (1996b) and Misra and Gibbons (1996) also reported an increase in the diameter of the root tip with increasing soil strength.

However, the above calculation was based on the assumption that maximum root growth pressure of radiata pine is around 1 MPa and wall yielding coefficient doesn't change with soil strength and there is no direct evidence to confirm these assumptions. This calculation just demonstrates a potential method to calculate P_s using this root growth model.

CHAPTER 7

PHYSIOLOGICAL RESPONSES OF PINUS RADIATA ROOTS TO SOIL STRENGTH AND WATER STRESS



Tru-Psi water potential psychrometer, Decagon Instrument, USA

7.1 Abstract

The osmotic potential, turgor pressure and yield turgor of the root cells in the elongation zone of radiata pine seedlings (i) cultured in PEG 4000 rooting medium of different water potentials and (ii) grown in soil of different strengths at the same soil matric potential were directly determined using a psychrometer. The roots osmotically regulated against both decreasing water potential of the rooting medium and increasing soil strength.

The results showed that there was no significant osmotic regulation at high water potentials in the rooting medium (> - 0.2 MPa). Osmotic adjustment commenced at about – 0.2 MPa water potential in the rooting medium. The osmotic regulation process could only partially adjust the turgor loss from water stress. The osmotic potential of the root cells fell approximately 0.3 MPa while the turgor pressure fell approximately 0.7 MPa over the range in water potential of the rooting medium from –0.01 MPa to – 1.0 MPa. Without osmotic regulation, the turgor pressure would have been zero at approximately – 1.1 MPa in the rooting medium. However, because of osmotic regulation, the turgor pressure was approximately 0.40 MPa at – 1.1 MPa in the rooting medium.

The roots osmotically adjusted against increasing soil strength. Turgor pressure increased by 0.10 MPa as a consequence of osmotic potential decreasing by the same amount as soil strength increased from 0.45 to 3.0 MPa.

The yield turgor pressure was independent of water potential of the rooting medium and soil strength. Wall yielding coefficient decreased with the water potential of the rooting medium. The root elongation rate decreased with water potential because of decreased turgor pressure and wall yielding coefficient.

Key words: *Pinus radiata* D. Don; root elongation rate; water stress; soil strength; osmotic regulation; turgor pressure; yield turgor; wall yielding coefficient

7.2 Introduction

Root elongation rate of radiata pine decreased with the decrease in the water potential of the rooting medium (Chapter 5). At low values of water stress (water potentials in the

rooting media > - 0.20 MPa), root elongation rate decreased linearly with decreasing water potential. However, the rate of decrease slowed at higher values of water stress (water potentials < - 0.20 MPa) which suggests that some physiological responses such as osmotic regulation may occur at higher values of water stress (Greacen and Oh, 1972).

Yau and Sands (1992) found that elm root suckers could osmoregulate against increasing soil strength and it is possible that this could also occur in roots as suggested by Dexter (1987).

Yau and Sands (1992) developed a model for root elongation in soil based on the model of Lockhart (1965) (see equation 5.5). If we accept this model, then decreasing soil matric potential and increasing soil strength will both decrease the root elongation rate but a decrease in osmotic potential (osmoregulation), an increase in wall yielding coefficient and/or a decrease in yield turgor could counteract this decrease. In this study, the possibility that roots can osmoregulate and/or change their yield turgors or wall yielding coefficient to compensate (fully or partly) for decreases in water potential or increases in soil strength are investigated.

7.3 Materials and Methods

7.3.1 Experimental Treatment

Radiata pine seedlings were cultured in PEG 4000 rooting medium with a range of water potentials of - 0.01, -0.03, -0.07, -0.1, -0.2, -0.5, -1.0 and -1.5 MPa as described in 5.3.2.1. There were 6 pots for each water potential treatment and three seedlings for each pot. Pre-germinated seeds of radiata pine were planted into pumice soil of different soil strengths at - 0.01 MPa water potential as described in 6.3. All samples were grown in controlled growth environment for 7 days (see 5.3 for details). In the

PEG rooting medium experiment it was assumed that the water potential of the PEG 4000 solution was equal to that of the root and that the mechanical impedance to root penetration, P_s, was zero.

Osmotic potential of root tissue at the elongation zone of the roots was measured by psychrometer using the stress relaxation technique described by Sands *et al.* (1992). The elongation zone in radiata pine roots is concentrated at 2 to 5 mm from the root tip (Youngman, 1998). Three mm root segments (cut from 2 – 5 mm from the root tip) were sealed into air-tight sample cups in the psychrometer. Under these circumstances the root cells of the elongation zone will keep elongating until the turgor pressure is equal to or balanced by the rigid cell wall, the yield turgor Y. At yield turgor, no water flows between cell wall (free water space) and the cell symplasm and elongation ceases ($\Delta R = 0$). It is assumed that the cell symplasm does not lose or gain solutes during incubation, and the value for Y can be determined from:

$$Y = \Psi_y - \Psi_{\pi y} \quad \text{(Sands } et\ al.\text{, 1992)} \tag{7.1}$$

where Ψ_y = the total water potential of root at yield, $\Psi_{\pi y}$ = osmotic potential of root tissue at yield. Both Ψ_y and $\Psi_{\pi y}$ can be directly determined, and then Y can be calculated.

Elongation of root cells in solution will dilute the cytoplasm by absorbing water from the rooting medium, and therefore the osmotic potential of elongated cells will increase (Sands *et al.*, 1992). In this study, root tissue was relaxed in sealed sample cups in a psychrometer*, and the osmotic potential of root cells both at harvest and after relaxation was analysed.

When yield turgor was determined, both the effective turgor pressure and wall yielding coefficient of the root tissue cultured in solution can be calculated as:

* TruPsi Water Potential Meter, Decagon Instrument, USA

$$\Delta P = P - Y = \Psi - \Psi_{\pi} - Y \quad (7.2)$$

$$\Phi = \Delta R / (P - Y) \quad (7.3)$$

7.3.2 Determination of Relaxation Time

At harvest, root segments of the elongation zone were dissected from the seedling roots and immediately placed into the psychrometer. The water potential of root tissues under relaxation was automatically measured every 30 minutes until a constant water potential was achieved under constant room temperature of 20^0C ($\pm$ 1^0C). There were 6 replicates. The water potential change of a wet soil sample of pumice was also monitored during the whole period as a control.

7.3.3 Osmotic Potential at Harvest

The psychrometer was used to determine the water potential of root tissue. At harvest, seedlings were removed from the solution or removed from the soil and cleaned using paper tissue. Root segments of the elongation zone were dissected from the seedling roots and were wrapped in aluminium foil and immersed into liquid nitrogen for one minute. The whole process was carried out as quickly as possible to minimise the water loss from the root tissue. Frozen root tissues were then placed into the sample cup of the psychrometer. Each sample cup contained 3 root tissues from the three seedlings in the same pot. The sample cups were then sealed in the psychrometer to thaw for one hour before the osmotic water potential of root tissue was determined.

7.3.4 Determination of Yield Turgor Pressure

After the root segments achieved total stress relaxation, the water potential of the root tissue was measured as the total water potential at yield (Ψ_y). After this water potential determination, the osmotic potential at yield was then determined using the method described in 7.3.2.

7.4 Results

7.4.1 Incubation Time for Stress Relaxation

When the root tips that were mainly composed of elongation cells were dissected from the seedling root, the root cells continued to elongate by absorbing water from the free space of cell walls. Therefore the water potential measured by the psychrometer continuously decreased (Figure 7.1). In contrast, the water potential of soil sample was almost constant because there was no water exchange, although a slight variation was observed due to the slight temperature fluctuation ($\pm$ 1 ^{0}C).

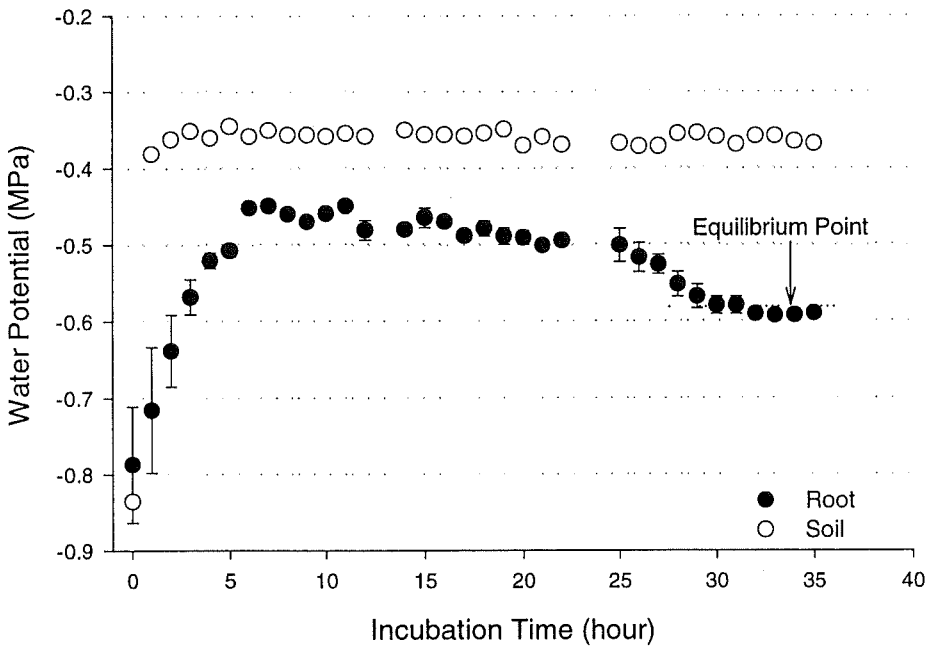


Figure 7.1. Relaxation time of root tissue in the elongation zone (± SE of the mean)

The psychrometer determined the water potential of the sample by measuring the vapour pressure around the sample space. When the root samples were placed into the sample cup, it took some time (1 - 2 hours) to establish the vapour equilibrium between

root samples and the initial dry sample cup space. This process was reflected in the rapid increase of water potential at the beginning. After this process, the water potential in soil was observed to be constant while the water potential of the root sample was observed to decrease because water in the cell wall free space was absorbed into the cytoplasm during the relaxation process. A water potential equilibrium was achieved after 30-35 hour's incubation (Figure 7.1). This indicated that the water exchange process had stopped and that the root cells had achieved full relaxation.

7.4.2 Osmotic Potential Change after Incubation

The osmotic potentials of root tissues growing in rooting medium of different water potentials were measured both at harvest and after incubation. The relationship between the osmotic potential determined at harvest and after incubation is given in Figure 7.2:

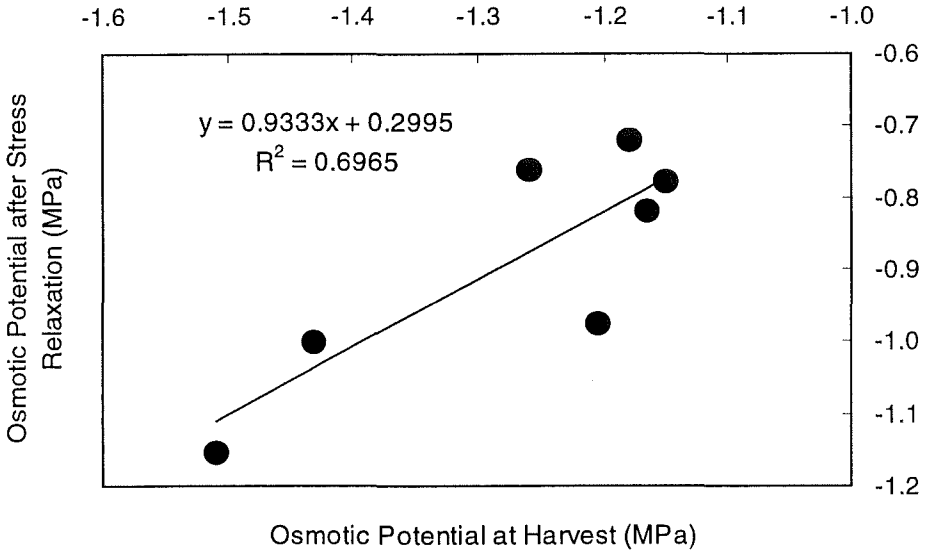


Figure 7.2. Comparison between the osmotic potential at harvest and after stress relaxation

The osmotic potential of the root cells increased by about 0.3 MPa after 35 hours incubation compared with the osmotic potential measured at harvest.

7.4.3 Osmotic Regulation and Water Stress

7.4.3.1 Osmotic Potential

The relationship between the osmotic potential of the root cells and the water potential of the rooting medium is shown in Figure 7.3. Comparison of means of root elongation rate (Duncan's Multiple Range Test) indicated that there was no significant relationship between the means of the osmotic potential of the root tissue and the osmotic potential of the root medium when the osmotic potential of rooting medium was higher than -0.20 MPa. However, the osmotic potential of root tissues decreased with the decreasing of osmotic potential in the rooting medium when the osmotic potential of rooting medium was lower than -0.20 MPa.

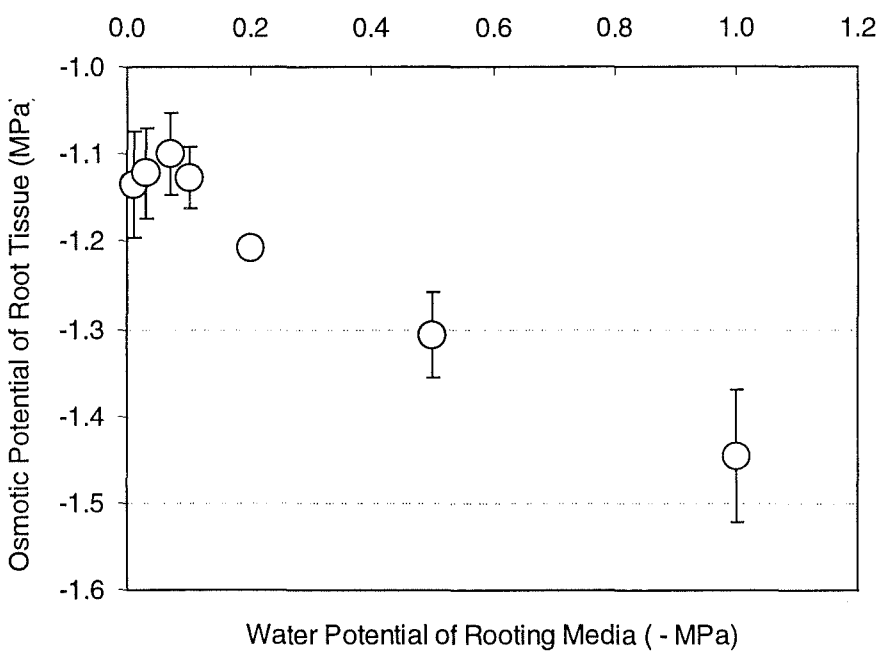


Figure 7.3. Osmotic potential of root tissues and the osmotic potential of the rooting medium (error bars are ± STD of the mean)

7.4.3.2 Turgor Pressure

The turgor pressure of the roots cultured in rooting medium was the difference of the osmotic potential of the rooting medium and the osmotic potential of the root tissue (Equation 7.2). The calculated turgor pressure decreased with the decrease of water potential of the rooting medium (Figure 7.4).

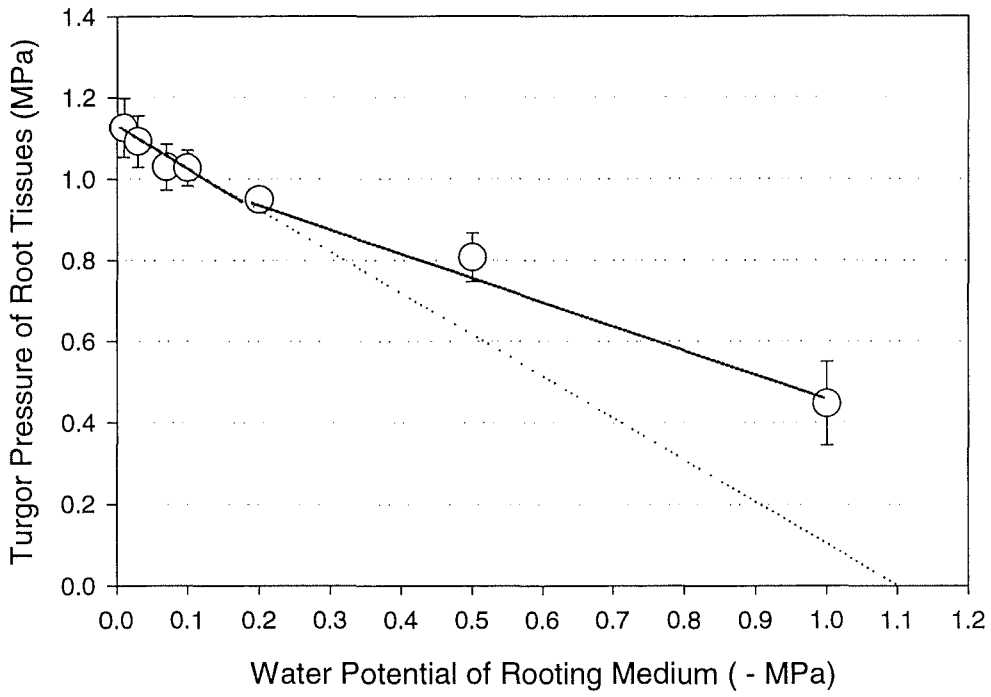


Figure 7.4. Turgor pressure as a function of the water potential of the rooting medium (error bars are ± STD of the mean)

When the osmotic potential of the rooting medium was higher than -0.20 MPa, the root cell turgor pressure decreased linearly with the decreasing of osmotic potential of the rooting medium. When the osmotic potential of rooting medium was lower than - 0.20 MPa, the decreasing rate of turgor pressure was slowed down. This indicated that an osmotic regulation process was induced to compensate for the loss in turgor pressure.

7.4.3.3 Yield Turgor (Turgor Pressure at Yield)

Yield turgor Y was calculated at each potential level using the equation 7.2. No statistically significant difference in the means of yield turgor was detected at each potential level (Duncan's Multiple Range Test). This indicated that yield turgor did not change with the water stress. The means of yield turgor calculated from all the data is given in equation 7.5:

$$Y = 0.35 \text{ MPa} \quad (STD = 0.03, n = 21) \tag{7.5}$$

7.4.3.4 Wall Yielding Coefficient (Φ)

Φ was then calculated from equation 7.3 and is listed in Table 7.1. Wall yielding coefficient decreased gradually with the decreasing of water potential of the rooting medium.

Table 7.1. Relationship between wall yielding coefficient of root cells at elongation zone (2 -5 mm) and the water potential of the rooting medium. Ψ_π = osmotic potential of rooting media (MPa), ΔR= root elongation rate (mm day^{-1}), Φ = wall yielding coefficient (mm day^{-1} MPa^{-1})

Ψ_π	ΔR (±STD)	Φ
-0.010	3.43±0.41	4.43
-0.030	3.31±0.31	4.46
-0.070	2.99±0.26	4.39
-0.100	2.96±0.36	4.30
-0.200	2.61±0.33	3.97
-0.500	1.40±0.45	3.06
-1.000	0.25±0.08	2.61

7.4.4 Soil Strength and Osmotic Regulation

7.4.4.1 Osmotic Potential Change of Root Tissue with Increased Soil Strength

The osmotic potential of root tissue grown in soil decreased with increase in soil strength (Figure 7.5):

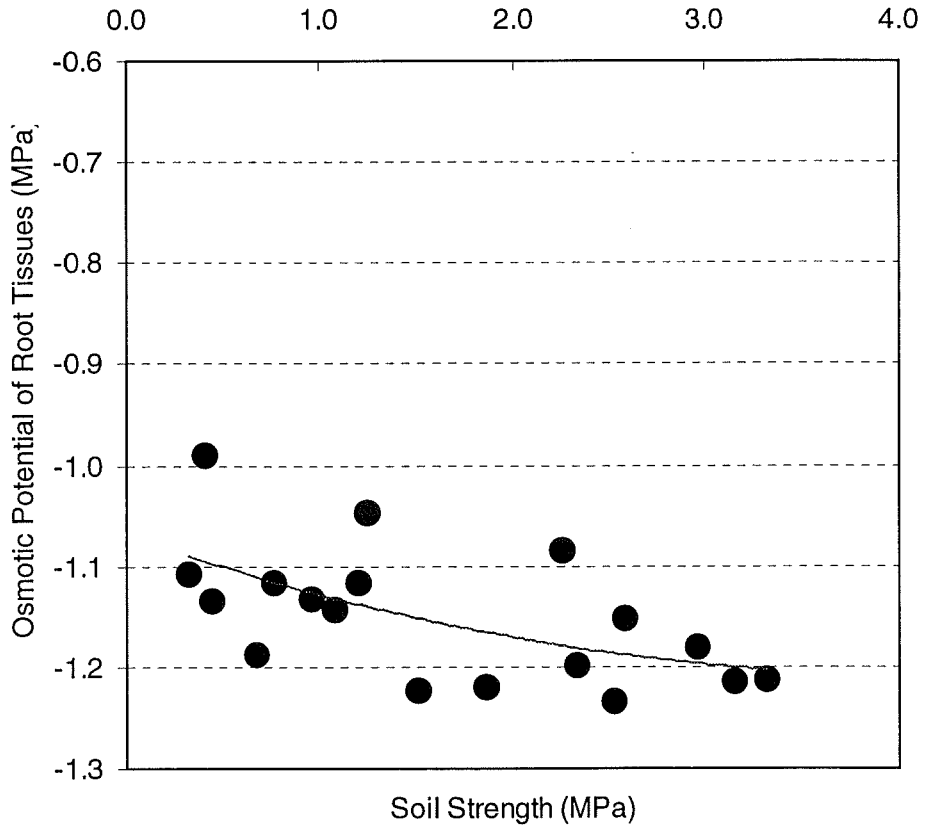


Figure 7.5. Relationship between the osmotic potential of root tissue and soil strength

The osmotic potential of root tissue decreased from -1.1 MPa at 0.2 MPa soil strength to about -1.2 MPa at 3 MPa soil strength (Figure 7.5).

7.4.4.2 Changes of Turgor Pressure and Yield Turgor with Increased Soil Strength

In the soil strength experiment, roots were grown at a constant soil matric potential (- 0.01 MPa). Assuming soil matric potential did not change during the experimental period (5.3.1), both turgor pressure and yield turgor were determined from equations 7. 1 and 7.2 and the results are shown in Figure 7.6:

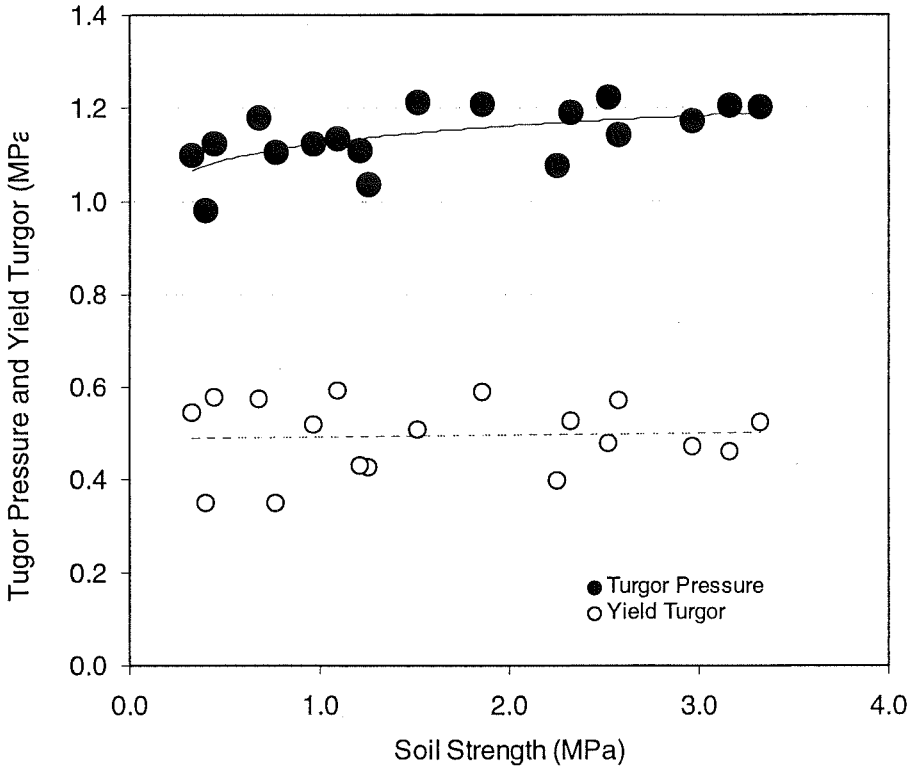


Figure 7.6. Turgor pressure and yield turgor of root tissue and soil strength

The turgor pressure of the root cells in the elongation zone increased with increasing of soil strength (Figure 7.6). This relationship can be written as the logarithm relationship (SAS NLIN):

$$\Psi_\pi = \beta \ln (Q) + \alpha \qquad (7.6)$$

where Ψ_π = osmotic potential of the root tissue, Q = soil strength, $\beta = 0.0528 \pm 0.018$, $\alpha = 1.125 \pm 0.013$ (DF = 17, RMS = 0.003)

When root elongation encountered high soil strength, it induced osmotic regulation to increase root turgor pressure by decreasing osmotic potential. The osmotic regulation process was more efficient at low soil strength. According to equation 7.6, root cell turgor pressure increased by 12.1, 15.8 and 17.9 % while soil strength increased from 0.10 to 1.0, 2.0 and 3.0 MPa respectively. Because the elongation of radiata pine roots was extremely restricted at soil strengths higher than 3.0 MPa, it was concluded that radiata pine roots can regulate turgor pressure up to around 2 fold in high soil strength (Equation 7.6). The magnitude of osmotic regulation was very limited compared with the 6 to 7 fold regulation calculated by Dexter (1987).

No statistically significant relationship between yield turgor pressure and soil strength was detected (p = 0.49).

$$Y = 0.49 \text{ MPa} \quad (STD = 0.018, n = 18) \tag{7.7}$$

7.5 Discussion

The equilibration times in this experiment were long (35 hours) and it is possible that there were some physiological changes that complicated interpretation of the results of yield turgor. Respiraton would have continued over the equilibration period. Another possible source of error in the calculation of yield turgor could be evaporation of water from the psychrometer cups over the long equilibration time. However, by using appropriate controls it was possible to show that water loss was negligible. However the equilibration time for osmotic potential was just one hour and there should be no complications from equilibration times for this measurement.

This study has shown that roots of radiata pine can osmotically regulate against decreasing water potential in a solution growth medium when mechanical impedance is zero. The osmotic potential of the roots cells fell approximately 0.3 MPa while the turgor pressure fell approximately 0.7 MPa over the range in water potential of the rooting medium –0.01 MPa to – 1.0 MPa (Figure 7.3 and 7.4). Osmotic adjustment commenced at about – 0.2 MPa water potential in the rooting medium. Without osmotic regulation, the turgor pressure would have been zero at approximately – 1.1 MPa (Figure 7.4) in the rooting medium. However, because of osmotic regulation, the turgor pressure was approximately 0.40 MPa at – 1.1 MPa in the rooting medium (Figure 7.4).

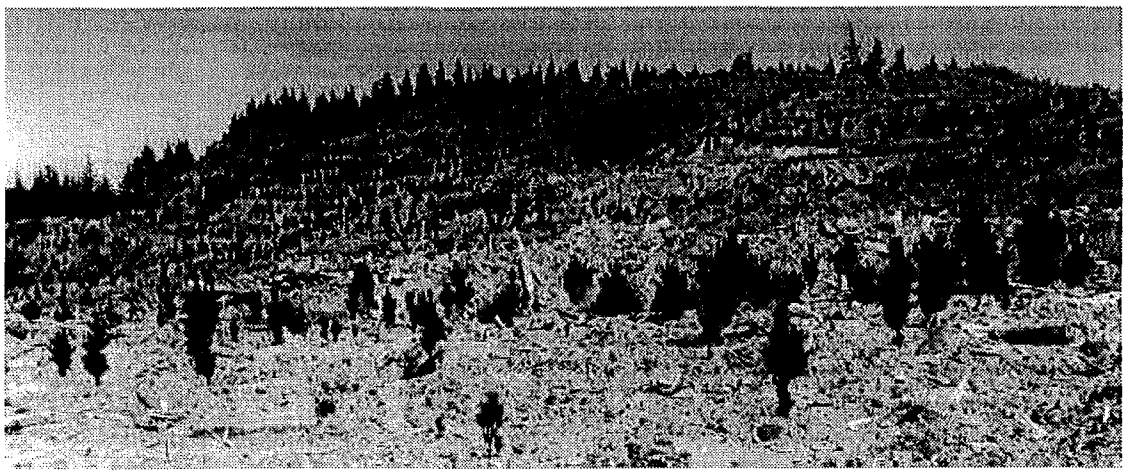
This study also showed that roots of radiata pine can osmotically regulate against increasing soil strength at constant (and high) soil water potential. The turgor pressure increased from 1.1 to 1.2 MPa (Figure 7.6) as a direct consequence of a decrease in osmotic potential from approximately – 1.1 to – 1.2 MPa (Figure 7.5).

Osmotic regulation is an energy driven process and any advantage in turgor maintenance would need to be offset against the energy cost of osmotic regulation.

There was no effect of increased water stress and increased soil strength on yield turgor. Because of this the problems associated with long equilibration times probably are not important in this study. Wall yielding coefficient (Φ) decreased with increasing water stress when the mechanical impedance was zero (Table 7.1). It is not possible to use equation 7.1 to calculate the effect of increasing soil strength on Φ because the relationship between soil strength (Q) and mechanical impedance (P_s) is not known for this experiment.

CHAPTER 8

INTERACTIVE INFLUENCE OF SOIL MATRIC POTENTIAL AND SOIL STRENGTH ON ROOT GROWTH OF PINUS RADIATA SEEDLINGS



Radiata pines grow poorly in compacted soil

8.1 Abstract

The root elongation rates of radiata pine (*Pinus radiata* D Don) seedlings were determined in a range of combinations of soil matric potential and soil strength using four soils of contrasting textures. When soil air-filled porosity was not limiting root growth, root elongation rate was due to the interactive effect of soil matric potential (Ψ_m) and soil strength (Q) and was best described by the model: $\Delta R = \alpha\, e^{-\beta Q + \gamma \Psi m}$. No significant effect from soil texture was observed.

Root growth is reduced in drying and compacted soils due to simultaneous effects of decreasing soil matric potential and increasing soil strength. The effect of water potential in decreasing root growth was most pronounced at low soil strength. Root growth of radiata pine seedlings ceased at higher soil matric potential in compacted soil than in loose soil.

Key words: *Pinus radiata* D Don; soil matric potential; soil strength; root elongation rate; modelling

8.2 Introduction

Root growth can be regarded as the integration of its internal physiological activities and its external environment. Soil aeration supplies O_2 to support the oxidation-energy-producing process. Soil strength helps resist soil compaction and to anchor the root system but it also is an opposing force to restrain root elongation. The uptake of soil water at favourable potentials is necessary for root growth and function but the amount of soil water also affects the aeration and strength of the soil, both of which also impact on root growth and function.

Soil air-filled porosity is related to soil matric potential and soil strength. A widely accepted opinion is that a soil air-filled porosity larger than 0.10 cm^3 cm^{-3} will not significantly restrict root growth of radiata pine (Sands and Bowen, 1978; Theodorou *et al.*, 1991; Xu *et al.*, 1992). More recent studies indicated that an air-filled porosity in excess of 0.16 cm^3 cm^{-3} is ideal for root growth of radiata pine in repacked soil (Penfold, 1998). This suggests that, providing soil aeration is kept above 0.16 cm^3 cm^{-3}, the effect of air-filled porosity can be isolated from soil matric potential and soil strength and it is possible to discuss the interactive effect of soil matric potential and soil strength on root growth without any complication from soil aeration.

In this study, soils of contrasting textures were chosen to establish a range of combinations of soil matric potential and soil strength at non-limiting air-filled porosity ($\geq$ 0.16 cm^3 cm^{-3}). A non-linear model approach was then used to establish the quantitative relationship between root elongation rate and soil matric potential and soil strength.

8.3 Description of Root Growth Data

Four soil types of contrasting textures were used in this study (Chapter 3). Each soil was repacked uniformly in 100 mm long, 48 mm ID stainless steel tubes to three bulk densities using the method described by Misra and Li (1996). The repacked soil samples were equilibrated in a pressure plate apparatus to 5 target matric potential levels (-0.01, -0.03, -0.07, -0.1, and -0.2 MPa). At water potential equilibrium, soil volumetric water content, and soil strength were determined and soil air-filled porosity was calculated. Three pre-germinated seeds of radiata pine were planted in each tube and grown for 7 days in a controlled climate condition (5.3.1.2). At harvest, root length was measured and root elongation rate was calculated as the average growth rate during the growing period. The water content of the soil sample was determined and the water potential, soil strength and air-filled porosity at harvest for each sample tube were calculated using soil moisture characteristic curves and soil strength characteristic curves (Chapter 4).

The root elongation rate was the average of the three seedlings in each tube. There were 180 observations of root elongation rate arising from 4 texture treatments $\times$ 5 potential treatments $\times$ 3 bulk density treatments $\times$ 3 tubes.

8.4 Methods

8.4.1 Selection of Model Parameters

8.4.1.1 Dependent Variable

Root growth might be described by root elongation rate, the total root biomass in the growth period and root diameter. Among them, root elongation rate (ΔR) was the best parameter to be associated with soil physical properties to represent root growth (5.4.2 and 6.4) and will be used as the dependent variable in this study.

8.4.1.2 Independent Variables

According to the recent findings of Penfold (1998), there is still a gradual increase in root elongation rate with increasing soil air-filled porosity when soil air-filled porosity is higher than 0.10 cm^3 cm^{-3}. However, there was no significant effect from aeration when air-filled porosity was larger than 0.16 cm^3 cm^{-3}, therefore all the observations with air-filled porosity smaller than 0.16 cm^3 cm^{-3} were deleted from the data set to exclude air-filled porosity from the model. Under the controlled experimental conditions, soil strength was relatively constant over time and the initially measured soil strength was used in the model (Figure 5.3.c). Soil matric potential decreased over the experimental period and the amount of decrease depended on texture and bulk density (Figure 5.3.d). Therefore the average of matric potential at planting and at harvest will be used in developing the model.

For the whole data set, there were four soil texture treatments, three bulk density treatments in each texture and three replicates for each bulk density. The effects of the treatments on variance were analysed using SASS anova. When there were no significant effects from soil texture, the observations from different textures were

treated equally. The effect from bulk density was represented by two independent variables - soil matric potential and soil strength - to establish the root growth model.

8.4.2 Model Selection

8.4.2.1 Model Definition

At a relatively high water potential (> - 0.20 MPa), root elongation rate (ΔR) decreased linearly with the decrease of soil matric potential (Ψ_m) at given soil strength (Equation 5.1), and the relationship between root elongation rate and soil strength (Q) was exponential at a given water potential (Equation 6.1). Root growth in soil is a combined result of these two factors and therefore the root growth may be represented by a simple model (Equation 8.1) assuming there is no interaction between these two factors:

$$\Delta R = \alpha e^{-\beta Q} + \gamma \Psi_m \qquad (8.1)$$

The effect of soil water potential might be associated with soil strength and a change of soil water potential may have a different effect at different soil strengths (Chapter 5; Glinski and Lipiec, 1990). This suggests that the coefficient relating soil water potential and root growth in Equation 8.1 is partially adjusted by soil strength and can be represented as γ/Q, and a potential model to describe this relationship is given as:

$$\Delta R = \alpha e^{-\beta Q} + (\gamma/Q)\Psi_m \qquad (8.2)$$

Roots of radiata pine could osmoregulate against water potential when water potential was lower than -0.20 MPa (7.4.3.1), and also against soil strength (7.4.4.1). Dexter (1987) showed that root growth ceased at higher matric potential in a stronger soil, and the effect of soil matric potential might be modifying the exponent ($-\beta Q$) of a root growth model developed at constant soil matric potential (Equation 6.1) as ($-\beta Q + \gamma \Psi m$). By doing so, the model will be able to be extended to a wider range of soil

matric potential. A potential model to describe this relationship is given as:

$$\Delta R = \alpha e^{-\beta Q + \gamma \Psi m} \quad (8.3)$$

8.4.2.2 Examination of the Models

The three models are non-linear, and SAS NLIN Procedure was used to regress both water potential and soil strength against root elongation rate. Residual mean square, skewness, kurtosis and residuals against predicted values were examined. The residual mean square, which is a measure of the unexplained error in a model, describes the goodness-of-fit of the regression. Skewness measures the tendency of the residual deviations to be larger in one direction than in the other. The values can be either positive or negative but ideally should be zero. Kurtosis measures the heaviness of the tails of the distribution of the residuals, and must lie between -2 and positive infinity. For a correct model residuals should be randomly scattered around zero and devoid of any pattern or trend with variation in the predicting variables.

8.5 Results

8.5.1 Model Parameters

Results of SAS anova analysis indicated that there were no significant effects from the texture treatments ($p = 0.59$) and tube treatments ($p = 0.94$) on root growth, and the only significant effect was due to the bulk density treatments ($p < 0.0001$).

The integrated effect of bulk density on root elongation rate was represented by soil air-filled porosity, soil water potential and soil strength. Using SAS GLM, the results showed that the effect of air-filled porosity on root elongation rate was not significant ($p = 0.79$), which indicated that the pre-determined air-filled porosity criterion of ≥ 0.16

$cm^3\ cm^{-3}$ was successful in excluding the effects from soil aeration. The root elongation rate was determined by soil water potential ($p = 0.0001$) and soil strength ($p = 0.0001$).

8.5.2 Model Adequacy

8.5.2.1 Comparison of Models

Values of residual mean square (RMS), skewness and kurtosis for the three models are given in Table 8.1:

Table 8.1. Statistical analysis of the three models

Model	Equations	RMS	Skewness	Kurtosis
8.1	$\Delta R = \alpha e^{-\beta Q} + \gamma \Psi_m$	1.91	-0.092	0.1623
8.2	$\Delta R = \alpha e^{-\beta Q} + (\gamma/Q)\Psi_m$	1.93	-0.2580	0.0759
8.3	$\Delta R = \alpha e^{-\beta Q + \gamma \Psi m}$	1.79	-0.0266	0.361

Among the three models, the smallest values of RMS, skewness, and an ideal value of kurtosis value were found for Model 8.3. This model is statistically the best of the three models to describe the relationship between root elongation rate and soil matric potential and soil strength.

8.5.2.2 Statistics of Model 8.3

The distribution of residuals against the predicted value for model 8.3 is shown in Figure 8.1:

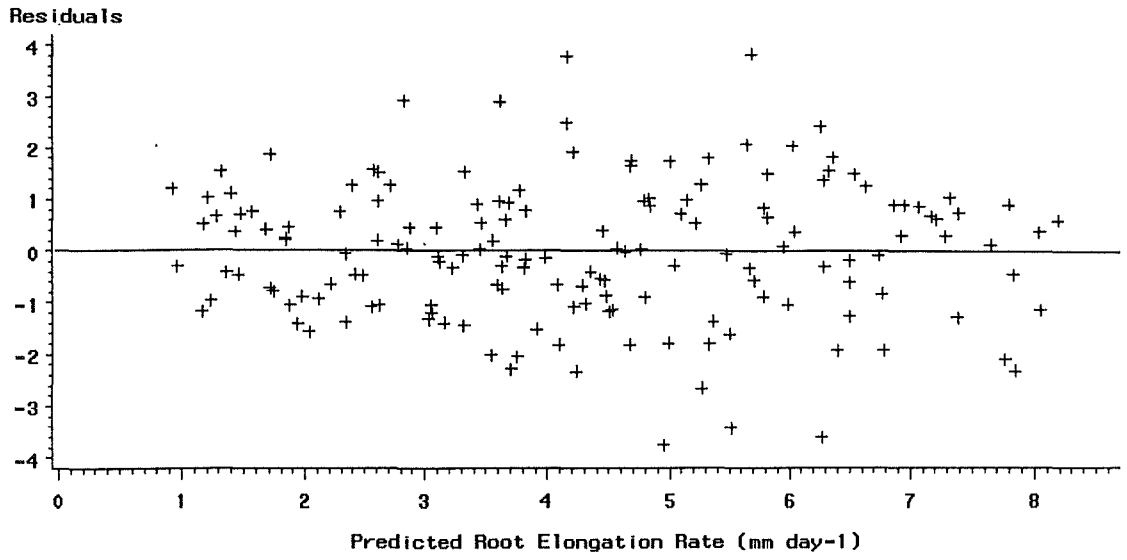


Figure 8.1. Pattern of residuals of root elongation rate versus prediction for Model 8.3

The predicted values of root elongation rate by Model 8.3 yielded a balanced residual distribution and was satisfactory. The parameter estimates of this model are given in Table 8.2:

Table 8.2. Estimated parameter values for Model 8.3

Parameter	Estimate	Asymptotic Std. Error	Asymptotic 95 % Confidence Interval	
			Lower	Upper
α	9.38	0.412	8.555	10.185
β	0.47	0.038	0.391	0.545
γ	1.75	0.300	1.161	2.347

The patterns of residuals of root elongation rate against matric potential and soil strength were also reasonable (Figure 8.2 and 8.3)

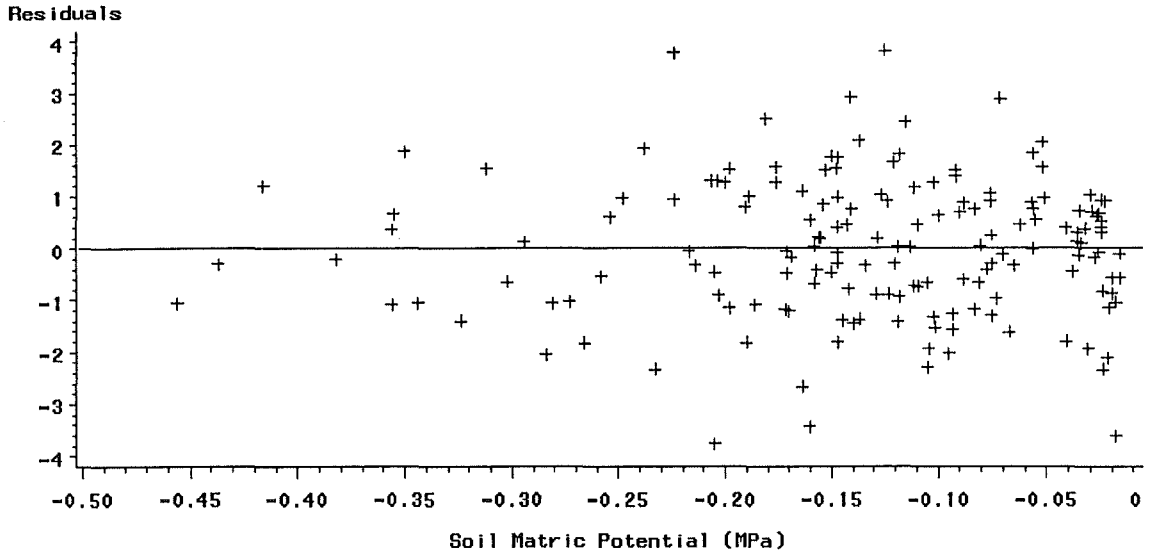


Figure 8.2. Pattern of residuals of root elongation rate versus soil matric potential for Model 8.3

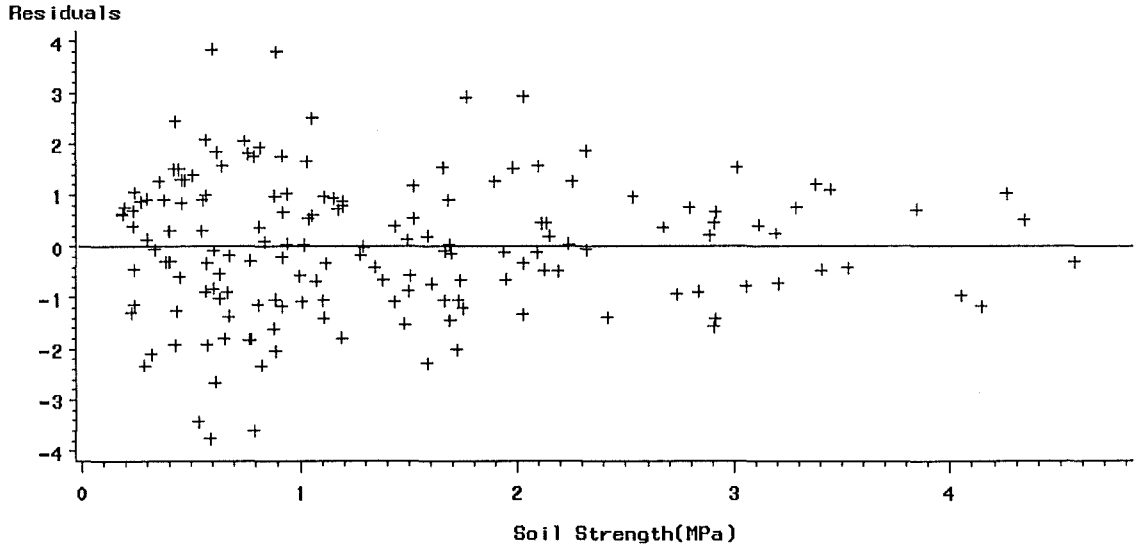


Figure 8.3. Pattern of residuals of root elongation rate versus soil strength for Model 8.3

Based on these statistics, the final root growth model is given as:

$$\Delta R = 9.38\, e^{-0.47Q + 1.75\Psi m} \quad (8.4)$$

$$\text{or } \ln(\Delta R) = 2.24 + 1.75\Psi_m - 0.47Q \quad (8.5)$$

8.5.3. Validation of Model

Measurements of root elongation rate against soil strength at -0.01 MPa matric potential were made in Chapter 6 for a pumice loamy sand soil (Figure 6.1). Using soil strength and matric potential as independent variables, the root elongation rates were predicted using Model 8.4 and the predicted root elongation rates from the model compared with the measured rates from Figure 6.1 are shown in Figure 8.4:

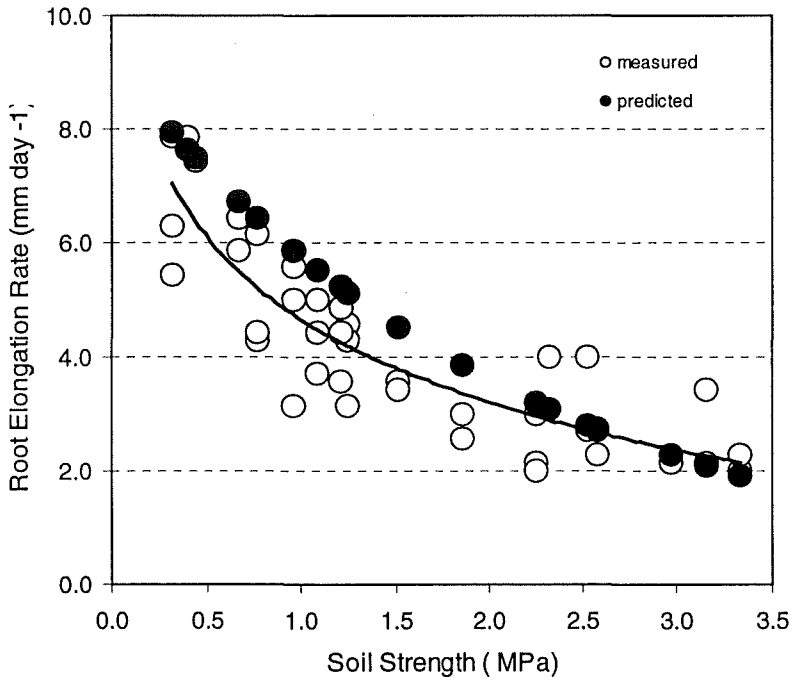


Figure 8.4. Comparison of directly measured root elongation rate with predicted root elongation rate by Model 8.4

Figure 8.4 showed that Model 8.4 can effectively predict the root growth over a range of

soil strength and the predicted data fit the measured data well at relatively high soil strength. The predicted data are marginally higher than the measured data at lower soil strengths, but it are reasonably close.

Davis (1984) studied the root elongation rate of radiata pine under different levels of soil water potential and soil strength using a sandy loam soil in a growth chamber at 25 ^{0}C for 5 days. Table 8.5 lists the root elongation rates given by Davis (1984) compared with those predicted by model 8.4:

Table 8.4. Comparison of root growth rates (mm day^{-1}) of radiata pine reported by Davis (1984) and predicted by Model 8.4

Ψ (MPa)	Q = 1.3 (MPa)		Q = 2.0 (MPa)		Q = 4.3 (MPa)	
	Davis (1984)	Predicted	Davis (1984)	Predicted	Davis (1984)	Predicted
> -0.1	5	5.00	3.4	3.60	1.2	1.22
-0.60	4.5	1.78	2.7	1.28	1.2	0.43
-1.5	3	0.37	1.8	0.27	1.2	0.09

At high water potentials (> -0.1MPa), the root elongation rates predicted by Model 8.4 were similar to the measured data reported by Davis (1984) at the three soil strength levels. However the predicted root elongation rate is significantly lower than the measured data when soil water potential < -0.10 MPa and the possible reason is given in the discussion.

8.6 Discussion

8.6.1 Root Growth Models

Simmons and Pope (1988) developed a root growth model to predict root response of yellow-poplar and sweetgum seedlings using soil bulk density (ρ_b,), air-filled porosity (ε_a) and soil strength (Q) in a silt loam soil (Model 8.6):

$$\Delta R = k + a\,\rho_b + b\varepsilon_a + c\,Q \qquad (8.6)$$

They reported that this model accurately predicted lateral root length and distribution for the range of soil properties used in their study. However, bulk density is closely related to air-filled porosity and strength, and is dependent on soil texture. The inclusion of bulk density as a parameter will complicate the influence from soil air and soil strength and restrict application of the model. Soil water condition is an important parameter to affect root growth, and exclusion of it from model is also inappropriate.

Dexter (1987) gave a root growth model mostly based on data from pea:

$$\Delta R / \Delta R_{max} = 1 + 0.78\Psi - 0.85P_s \qquad (8.7)$$

where ΔR_{max} is the maximum rate of root elongation (mm day^{-1}) and P_s is soil mechanical impedance to root elongation (MPa)

The root growth model given in this study (Model 8.5) is similar in structure to Dexter's model (8.7). Both models demonstrate the negative effects of decreased soil matric potential and increased soil strength on root elongation rate. However, soil mechanical

impedance to root elongation (P_s) in Model 8.7 is difficult to be determined directly, therefore this might restrict its practical application. In contrast, both water potential and soil strength in Model 8.5 can be directly measured. For a given soil at a given bulk density, water potential and soil strength are functions of volumetric water content, and Model 8.5 can be further simplified to simulate root growth against soil volumetric water content.

8.6.2. Validation of Model 8.4 to Independent Data

8.5.3 demonstrated that Model 8.4 was successful in predicting root elongation rates from an independent data set used in Chapter 6. The predicted root elongation rates at relatively low soil strength range (< 1.5 MPa) were slightly higher than the measured data, but is within the model prediction error (1.79 mm day^{-1}). The reason for this error might be because the soil matric potential used for prediction was the initial water potential. The actual water potential should be lower than the initial value and the predicted values are likely to under-estimate the effect of soil water potential.

At high water potential (> -0.1MPa), the root elongation rates predicted by Model 8.4 are similar to the measured data reported by Davis (1984) at the three soil strength levels. However the predicted root elongation rate is significantly lower than the measured data when soil water potential < -0.10 MPa. In Davis (1984), the water potential was achieved by wetting soil to the water content calculated from the water characteristic curve. The actual water potential achieved by this method might be significantly higher than designed because of strong hysteresis in the soil moisture characteristic curves, especially in a coarse-texture soil and at lower water potential levels. Therefore the values of water potential demonstrated by Davis (1984) are questionable. This might also explain why Davis's data showed that the root elongation rate was still very high even at wilting point (-1.5 MPa) at three soil strength levels.

8.6.3 Soil Drying and Root Growth

When soil is drying, root growth decreases. The root growth is the interactive effect of increased soil strength and decreased water potential if there is no aeration restriction. The root growth model (Model 8.4) clearly demonstrates the details of the interacting process of soil matric potential and soil strength on root elongation of radiata pine (Figure 8.4):

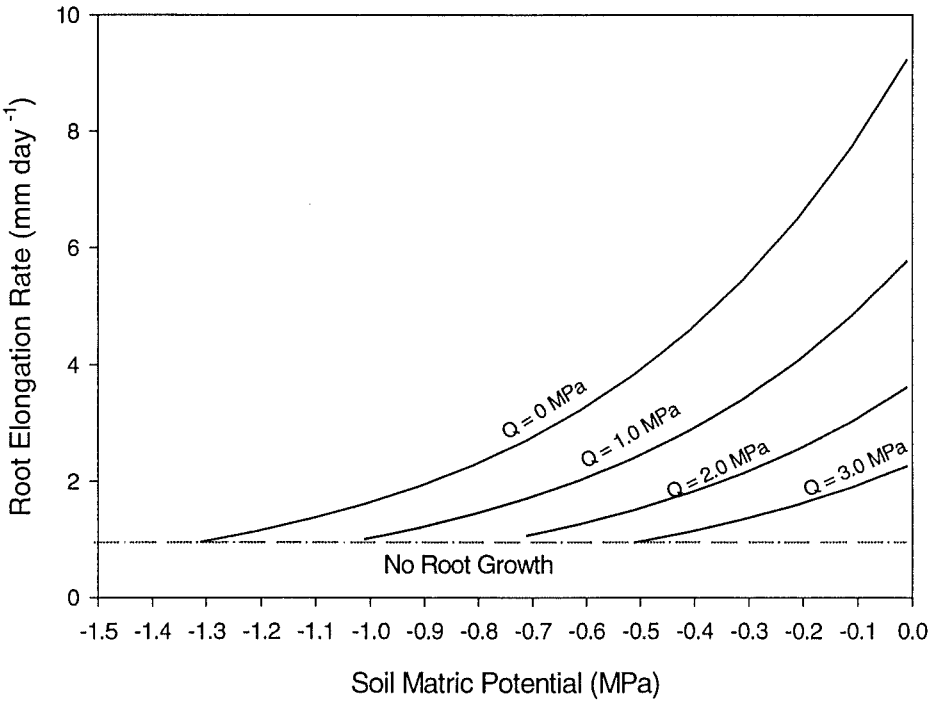


Figure 8.5. Values of root elongation rate under combinations of conditions of soil matric potential and soil strength predicted from Model 8.4

When root elongation rate was smaller than 1 mm day^{-1}, the measured root elongation rate was largely subject to the measurement error during a short growth period like in this study and it was defined arbitrarily as no root growth in this discussion. When soil

strength was zero, then root growth ceased at a soil matric potential of -1.30 MPa, which is close to the wilting point. The soil matric potential where root growth ceased increased with increasing soil strength in a manner similar to that reported by Dexter (1987).

At each level of soil strength, the root elongation rate decreased exponentially with decreasing soil matric potential. The effect of soil matric potential in decreasing root growth was most pronounced at high water potential. Over a relatively high matric potential range (-0.01 to -0.20 MPa), the relationship was close to linear (Figure 8.5). The exponents of these curves decreased with increasing soil strength, and this suggests that the effect of soil matric potential on root growth is dependent on soil strength and the change of soil matric potential has a greater effect on root growth in loose soil than in compacted soil (Dexter, 1987).

However, in the rooting medium, the root growth of radiata pine was found to decrease logarithmically with decrease of water potential of rooting medium (5.4.3). The difference of the effect of water potential on root elongation rate between rooting medium and soil might be explained as the interactive effect from soil strength in soil.

8.6.3. Soil Matric Potential and Maximum Root Penetration Soil Strength

Dexter (1987) showed that root growth ceased at less negative values of soil matric potential in strong soil. Assuming root growth ceased when root elongation rate was equal to or less than 1 mm day $^{-1}$ (ln ΔR=0), the maximum soil strength that roots can effectively penetrate was calculated from the root growth model (Model 8.5) and is given in Figure 8.6:

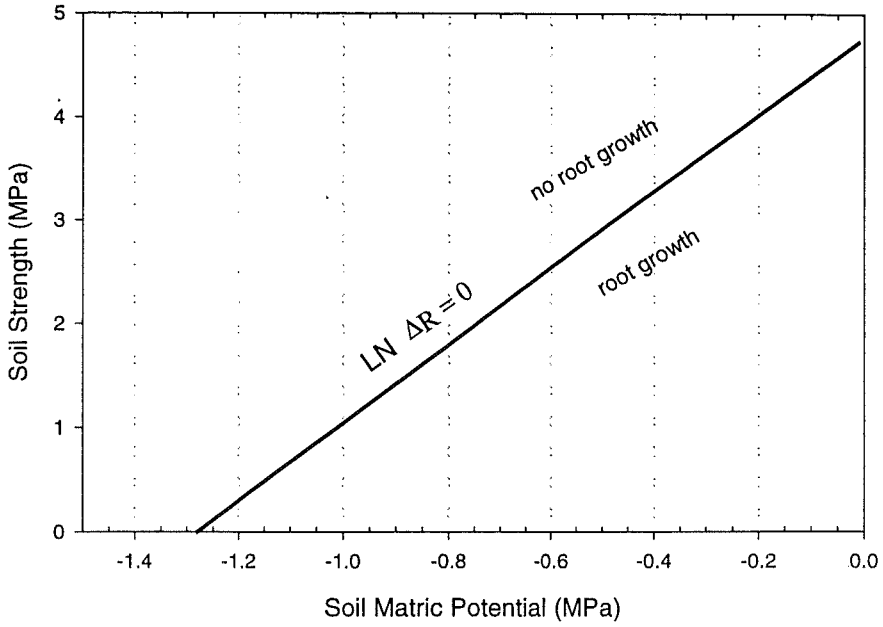


Figure 8.6. Soil matric potential and maximum soil strength roots can penetrate

The maximum soil strength roots of radiata pine can penetrate is positively related to soil matric potential. Roots can effectively penetrate soils with strength as high as 4.7 MPa at a favourable soil matric potential (-0.01 MPa). However root growth will cease at soil strength of 3 MPa at a soil matric potential of -0.45 MPa or lower. This result is similar to the result reported by Dexter (1987) on root growth of peas.

CHAPTER 9

CONCLUSIONS AND SUGGESTIONS

9.1 Conclusions

This thesis has clearly demonstrated the quantitative relationship between soil matric potential and the primary root growth of radiata pine (*Pinus radiata* D Don) without complication from soil strength and soil air-filled porosity (chapter 5). This thesis also established the quantitative relationship between soil strength and the primary root growth of radiata pine without complication from soil matric potential and soil air-filled porosity (chapter 6). The physiological responses of primary roots of radiata pine to decreased water potential and increased soil strength were also investigated in both soil and rooting medium (chapter 7). Based on these results, a root growth model incorporating soil matric potential and soil strength was developed and its capacity to simulate the root growth was demonstrated (chapter 8).

Primary root growth decreased with decreasing water potential due to the loss of turgor pressure and the decrease of the cell wall yielding coefficient (7.4.3). At a relatively high soil matric potential range (-0.01 to –0.20 MPa), the root elongation rate decreased linearly with decreasing soil matric potential (5.4.2). Moderate and high water stress (< -0.20 MPa) induced roots to decrease their osmotic potential to counteract the loss of turgor pressure (7.4.3.2). However the osmotic adjustment could only recover a part of loss of turgor pressure. Water stress also decreased the cell wall yielding coefficient

(7.4.3.4). As a result of the partial loss of turgor pressure and the decrease in the cell wall yielding coefficient, the root elongation rate decreased logarithmically with decreased water potential (5.4.3).

Primary root growth decreased exponentially with increased penetrometer soil strength (6.4.1) and this was independent of soil texture (6.4.4). The elongation rate of primary roots of radiata pine was reduced to half of its maximum elongation rate at 1.4 MPa penetrometer soil strength, which is normally not regarded as very high soil strength. Consequently, forest productivity might be reduced by relatively low values of soil strength in soils that are normally not considered to be compacted. The roots increased their turgor pressure to counteract an increase in soil strength (7.4.4.2). However, the increase in turgor pressure was only around 0.20 MPa when the soil strength increased from 0 MPa to 3.0 MPa. Therefore the osmotic regulation mediated the effect of increased soil strength only to a minor degree (7.4.4.2).

When soil air-filled porosity was non-limiting, root elongation rate in soil (ΔR) was determined by soil matric potential (Ψ_m) and soil strength (Q) and was best described by a non-linear model: $\Delta R = \alpha\, e^{-\beta Q + \gamma \Psi m}$ (8.5.2). The effect of water potential in decreasing root growth was most pronounced at low soil strength. Roots of radiata pine were able to penetrate higher soil strength at higher soil matric potential, and root growth of radiata pine seedlings ceased at higher soil matric potentials in compacted soil than in loose soil (8.6.3).

Soil physical properties directly affected root growth, and the main soil physical properties were associated with soil texture and varied with soil bulk density and soil water content. Soil matric potential decreased exponentially with the decrease of soil volumetric water content (4.3.2). Increasing soil bulk density (compaction) decreased soil matric potential at a given volumetric water content (4.3.2). It was easier for roots to extract water from a coarse-textured soil than from a fine-textured soil at the same volumetric water content at a comparable bulk density (4.4.2). Increasing the bulk density of a soil made it behave like a finer-textured soil and it was easier for a root to

extract water from a lower bulk density soil than from a soil of a higher bulk density at the same water content (4.3.2). Soil strength increased logarithmically with the decrease of soil volumetric water content (4.3.3) and soil strength increased with increasing bulk density at the same water content (4.3.3). Increase of bulk density had a greater effect of increasing soil strength in coarser soil than in finer soil but decrease of soil water content had a greater effect on increasing soil strength in finer soil texture than in soil of coarser texture (4.4.2). In addition, drying soil caused greater increase in soil strength in an already high strength soil than a lower strength soil, particularly in finer soils. Conversely, watering a dry compact soil caused a greater reduction in soil strength than watering a relatively non-compact soil, and particularly a fine soil (4.4.2). The practical implications are that traffic will compact a coarse soil to values of soil strength that do not differ greatly with soil water content. Adding water to a dry coarse soil will do little to reduce soil strength. The reduction of soil strength in compacted coarse soils can be achieved best by reducing soil bulk density by mechanical means. In fine textured clay soil, traffic ideally should be confined to dry soils where the soil strength is already high and therefore will therefore resist compaction. The high soil strength will be reduced when the soil is wet (4.4.2).

9.2 Suggestions

The ability to simulate root growth in intact soil is limited since most of methods used to measure root growth will destroy soil or modify the natural soil environment. However, for a given tree species, root growth is a compound result of the effects of soil water, soil aeration, the mechanical impedance of soil to root penetration, soil pH, soil nutrient condition and soil temperature. If the relationship between root growth and these single properties and their interactions are established, then root growth in an intact soil environment (where these properties are compounded) can be simulated. This thesis has attempted to use soil matric potential and soil strength to simulate the root growth of radiata pine while maintaining the above-mentioned other physical and chemical properties at non-limiting or optimum conditions. This is just the starting

point for a further sophisticated model which would take the additional factors into account. An exponential model was established which demonstrated its capacity to simulate the primary root growth at non-limiting air-filled porosity, non-limiting nutrient conditions and controlled soil temperature regime. However the root growth in a natural environment will experience different soil aeration, soil nutrient conditions and soil temperature fluctuations, and their physical and chemical properties might interact strongly. Further, a root growth model taking all these factors into account is required to have the capacity to simulate root growth *in situ.*

Individually, soil physical factors have been used as indicators of the suitability and sustainability of the soil for plantation establishment. However, as demonstrated in this thesis, the effect of soil physical properties on root growth is an integrated effect rather than the effect of single factor operating independently. A surrogate of these physical properties which takes their direct effects on root growth of a certain species into account would better reflect the suitability and sustainability of a soil for plantation production. One such indicator which connects a number of soil physical properties is the Least Limiting Water Range (LLWR) (da Silva *et al.*, 1994). LLWR defines the upper limit of water available to plants by either the water content at field capacity or some value of limiting air-filled porosity (say 10%) whichever is the lesser, and the lower value of available water as the water content at wilting point or at some limiting value of soil strength (say 3.0 MPa), whichever is the greater. This thesis has shown that it is simplistic to assume an arbitrary value for non-limiting soil strength because the relationship between root growth and soil strength is a continous exponential decrease (6.4.1). However, LLWR could still be a valuable soil quality indicator when used for monitoring changes in a particular soil over time.

The soil physical environment will affect the above-ground biomass as well as root growth and root system development. Usually biomass is partitioned so that the above ground parts are favoured when soil resources (water and nutrients) are not limiting relative to above-ground resources (light), and vice versa (Sands and Mulligan, 1990). It is possible that increased root growth promoted by more favourable soil strength

and/or improved soil aeration could result in greater efficiency of water and nutrient uptake which could translate into relatively more photosynthate being partitioned into the above-ground biomass. It does not necessarily follow, therefore, that roots systems in well aerated and/or low strength soils will be extensive.

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APPENDIX 1

N.Z. FOREST RESEARCH INSTITUTE FOREST NUTRITION LABORATORY REPORT

Forest Nutrition Laboratory Report
Forest Technology Division
N.Z. Forest Research Institute (Soil Test)
Private Bag 3020
Rotorua

Table 1A-1. Nutrient analysis of four soil types

Log No.			S19139	S19140	S19141	S19142
Description			Ash	Pumice	Loess	Argillite
Total N		(g/100g)	0.508	0.104	0.084	0.289
Bray-P	1	(mg/kg)	22.59	8.27	2.39	11.92
Bray-P	2	(mg/kg)	21.17	12.17	1.74	6.99
Bray-P	3	(mg/kg)	15.87	25.21	2.47	5.97
Bray K		(cmol/kg)	0.39	0.11	0.09	0.54
Bray Ca		(cmol/kg)	7.59	0.95	0.84	3.94
Bray Mg		(cmol/kg)	1.06	0.08	1.59	1.6

Comments:

S1: Soil pH is satisfactory for radiata pine. The soil N value is in the "high" range for radiata pine, and Bray P values indicate adequate P status for radiata pine. The Bray cation values are adequate.

S2: Soil pH is satisfactory for radiata pine. The soil N value is low and for radiata pine N fertiliser will be required. The Bray P values are behaving in a typical way for ash

soils -increasing Bray P values with succeeding extractions. The mechanism behind this effect has not been investigated. The Bray K value for this site is low, but since the correlation between Bray K and radiata pine K nutrition is poor, this low value does not necessarily mean K nutrition will be a problem. The Bray Mg value is critically low, and Mg fertiliser will be required to maintain radiata pine Mg nutrition.

S3: Soil pH is satisfactory for radiata pine. However, soil N values are critically low, as are the values for Bray P. Both N and P fertilisers will be required to maintain radiata pine N and P nutrition. Bray K values are extremely low, and K fertiliser will be required to maintain pine K nutrition.

S4: Soil pH is satisfactory for radiata pine. The soil N value is satisfactory for radiata pine and soil P fertility is probably just adequate, at least until canopy closure; beyond this time foliar P values should be monitored. The Bray cation status is adequate.

APPENDIX 2

CALIBRATION OF THE PSYCHROMETER

The psychrometer (TruPsi Water Potential Meter, Decagon Instruments, USA) was calibrated by using standard sodium chloride solutions with a range of molal concentrations. The relationship of water potential and the molality of sodium chloride solution at 20 ^{0}C was given by Lang (1967) as the following:

Table 2A-1. Water potential of sodium chloride solution at 20 ^{0}C (Lang, 1967)

Molality (mol/l)	Concentration (g/l)	Water Potential (MPa)
0.05	2.922	-0.230
0.1	5.844	-0.454
0.2	11.688	-0.900
0.3	17.532	-1.344
0.4	23.376	-1.791
0.5	29.220	-2.241

The empirical water potentials of sodium chloride solutions at 6 concentrations as listed in Table 2A-1 and a distilled water control were measured using the psychrometer. The standard water potentials of these solutions (empirical values from Table 2A.1 and the standard water potential of distilled water is assumed to be 0 MPa) and the water potentials measured by psychrometer (psychrometer value) are given in Figure 2A-1:

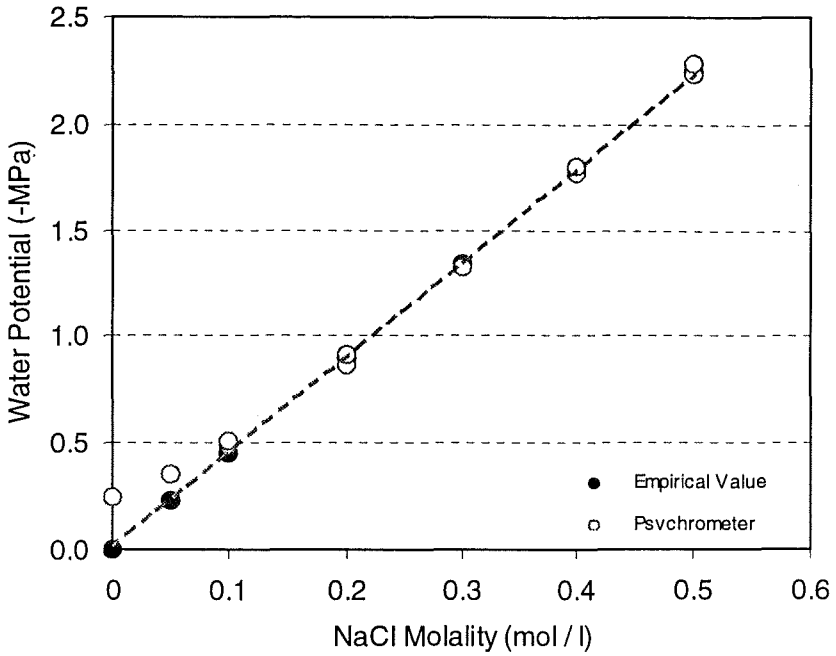


Figure 2A1. Calibration of psychrometer in standard NaCl solution of known water potentials and distilled water

This Psychrometer has a very good precision in measuring water potentials lower than - 1.0 MPa, and the precision decreased when water potential was higher than - 1.0 MPa. A significant difference between the empirical water potential value and the values measured by psychrometer occured at water potentials higher than -0.5 MPa (Figure 2A.2).

Using SAS NLIN procedure, this relationship was given in the following non-linear model:

$$\Psi_{empirical} = -\alpha + \beta \ln(\Psi_{psychrometer}) \quad \text{while } \Psi_{psychrometer} > -1.0 \text{ MPa} \quad (2A.1)$$

$$(RMS = 0.006, \alpha = 0.856 \pm 0.089, \beta = 0.735 \pm 0.051)$$

where $\Psi_{empirical}$ is the actual value of water potential, and $\Psi_{psychrometer}$ is psychrometer value of water potential.

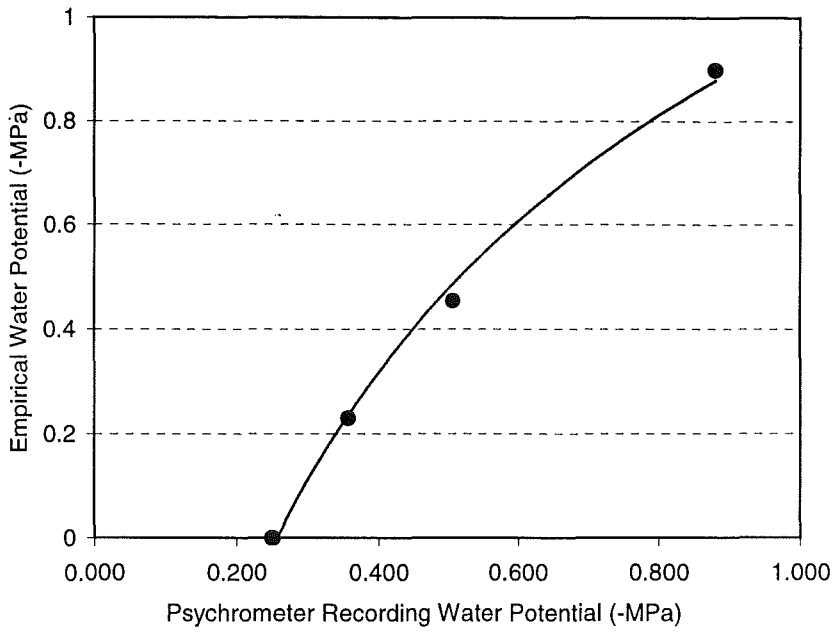


Figure 2A-2. Relationship between empirical water potentials and psychrometer recording water potential at water potential higher than -1.0 MPa

When the water potential measured by this psychrometer is higher than -1.0 MPa, the measured water potential must calibrate against Equation 2A.1 to get the actual water potential value.

APPENDIX 3

OSMOTIC WATER POTENTIALS AND PEG 4000 SOLUTION CONCENTRATIONS

Polyethylene Glycol 4000 (PEG 4000) was dissolved into distilled water to eight concentrations (Table A3.1.). The osmotic water potentials of the solutions were determined by a psychrometer and there were three replicates for each concentration. The results are given in Table A3.1:

Table A3.1. Measured osmotic potentials in a range of PEG 4000 solution concentrations

Molality (mol/litre)	Osmotic Potential (MPa)		
	Replicate 1	Replicate 2	Replicate 3
0.07	1.650	1.630	1.630
0.06	1.150	1.160	1.162
0.05	0.822	0.822	0.822
0.04	0.470	0.482	0.482
0.03	0.266	0.262	0.270
0.02	0.203	0.209	0.191
0.01	0.060	0.076	0.076
0.005	0.027	0.036	0.035

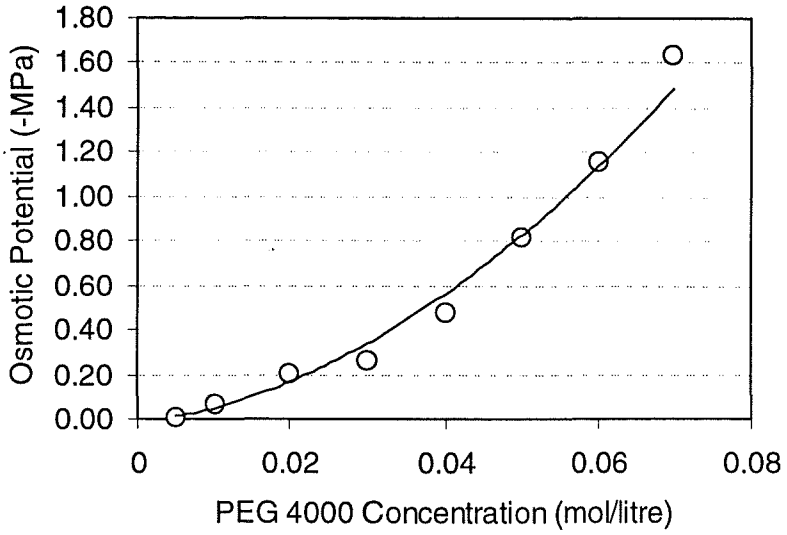


Figure A3.1. Relationship between osmotic potentials and the PEG 4000 solution concentrations

Using SAS NLIN procedure, this relationship was given in the following model:

$$C_{peg} = \alpha \Psi_{\pi}^{\beta} \qquad \text{(A3.1)}$$

(RMS= 7.6×10^{-6}, $\alpha = 0.0549 \pm 0.0007$, $\beta = 0.55 \pm 0.019$)

where C_{peg} is the PEG 4000 concentration (mol/litre), and Ψ_{π} osmotic water potential (-MPa).

Based on Equation A3.1, the PEG 4000 concentrations for given osmotic water potentials were calculated and are listed in Table A3.2.

Table A3.2. List of PEG 4000 concentrations (C) required for a certain osmotic potential (Ψ_π) calculated from Equation A3.2

Ψ_π (MPa)	C (mol/litre)	Ψ_π (MPa)	C (mol/litre)	Ψ_π (MPa)	C (mol/litre)
-0.010	0.0044	-0.200	0.0227	-1.200	0.0607
-0.020	0.0064	-0.300	0.0283	-1.300	0.0634
-0.030	0.0080	-0.400	0.0332	-1.400	0.0661
-0.040	0.0093	-0.500	0.0375	-1.500	0.0686
-0.050	0.0106	-0.600	0.0415	-1.600	0.0711
-0.060	0.0117	-0.700	0.0451	-1.700	0.0735
-0.070	0.0127	-0.800	0.0486	-1.8	0.0759
-0.080	0.0137	-0.900	0.0518	-1.9	0.0781
-0.090	0.0146	-1.000	0.0549	-2	0.0804
-0.100	0.0155	-1.100	0.0579	-2.1	0.0826

APPENDIX 4

MG5/K20 NUTRIENT SOLUTION

4.1. Mg5/K20 Nutrient Solution Composition

Sun and Payn (1999) gave a Mg5/K20 nutrient solution for culture of radiata pine (Table A4.1).

Table A4.1. The compound and the amount of each compound for making base solutions for Mg5/K20 nutrient solution

Compound	Amount (g)
Base solution A	**1 litre**
HNO_3	1.6 ml
$Ca(NO_3)_2.4\ H_2O$	20.6
$Mg(NO_3)_2.\ 6\ H_2O$	26.7
$Fe_2(SO_4)_3$	1.25
$MnSO_4.4\ H_2O$	0.81
H_3BO_3	0.57
$CuCl_2.2H_2O$	0.036
$ZnSO_4.7\ H_2O$	0.066
Base solution B	**1 litre**
NH_4NO_3	89.4
KNO_3	25.8
$(NH4)_2SO_4$	16.8
$(NH4)_2HPO_4$	27.7

Addition of 2 ml base solution A and 2 ml base solution B into distilled water and made up to 1 litre by adding extra distilled water gives a nutrient solution with 100 mg/l nitrogen concentration.

Different nitrogen concentrations were achieved by diluting the base solution to different volumes.

4.2. Osmotic Water Potential of Mg5/K20 Nutrient Solution

The osmotic potentials (Ψ_π) of Mg5/K20 nutrient solutions of different nitrogen concentrations were measured using the psychrometer and the relationship between osmotic potential and nitrogen concentration is given in Figure 4A-1:

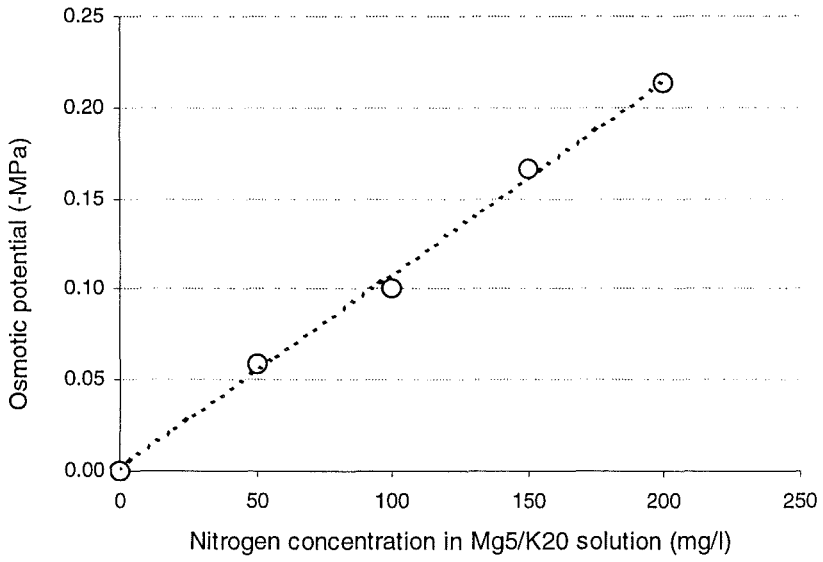


Figure A4.1. The relationship between osmotic potentials and nitrogen concentrations of Mg5/K20 nutrient solution

The osmotic potential (Ψ_π) of Mg5/K20 nutrient solution is linearly related to the nitrogen concentration (N, mg/l) of nutrient solution:

$$\Psi_\pi = 0.0011C + 0.0009 \quad (R^2 = 0.9975) \qquad (A4.1)$$

APPENDIX 5

NUTRIENTS AND ROOT GROWTH OF RADIATA PINE SEEDLINGS

In order to make sure that the root growth of radiata pine seedlings in rooting medium is healthy and is not seriously affected by the deficiency of nutrients, addition of nutrients into the rooting medium is required. However addition of nutrients will decrease the osmotic potential of the rooting medium. According to Dr Osbert Sun (personal communication), a Mg5/K20 nutrient solution with 25 - 50 mg/l nitrogen concentration is ideal for seedling growth of radiata pine cultured in solution rooting medium. However according to Equation A5.1, the water potential of a Mg5/K20 nutrient solution with 25 mg/l nitrogen concentration is equal to - 0.0284 MPa. The highest water potential treatment in this experiment is -0.01 MPa, which is equal to a Mg5/K20 nutrient solution with 8.3 mg/l nitrogen concentration.

To minimise the Mg5/K20 nutrient solution concentration requirement for culturing radiata pine seedlings, a potential method is to replace the rooting medium more frequently. This experiment investigated the effect of four Mg5/K20 nutrient solution treatments on root growth when the nutrient solutions were replaced every second day.

Pre-germinated radiata pine seeds (see 5.3.1) were planted in a sand bed until the root was about 20 mm long, and then these seedlings were transferred into Mg5/K20 nutrient solution with 8.3 mg/l nitrogen to grow until the needles of seedlings were fully opened. The root length was measured and marked with water resistant ink pen at 2 cm from the root tip. These seedlings were then transferred into 500ml plastic pots containing Mg5/K20 solution of 8.3 mg/l, 12.5 mg/l, 25 mg/l and 50 mg/l nitrogen or distilled water (control). Three seedlings were anchored separately into the 3 of the 4 pre-drilled 1.2 mm ID holes on the lid with Blue Tak. The fourth hole at the centre was left as an

air-escape. A 5 mm ID hole was drilled for an air-pump hose. All the pots were connected to a pumping system to maintain ideal aeration (Chapter 5).

The seedlings were grown in the pot for 7 days in a controlled environment cabinet as described in 5.3.1.2. At harvest, the primary root length was measured and the root elongation rate was calculated as the average root growth rate during the experiment period. The result is given in Figure A5.1:

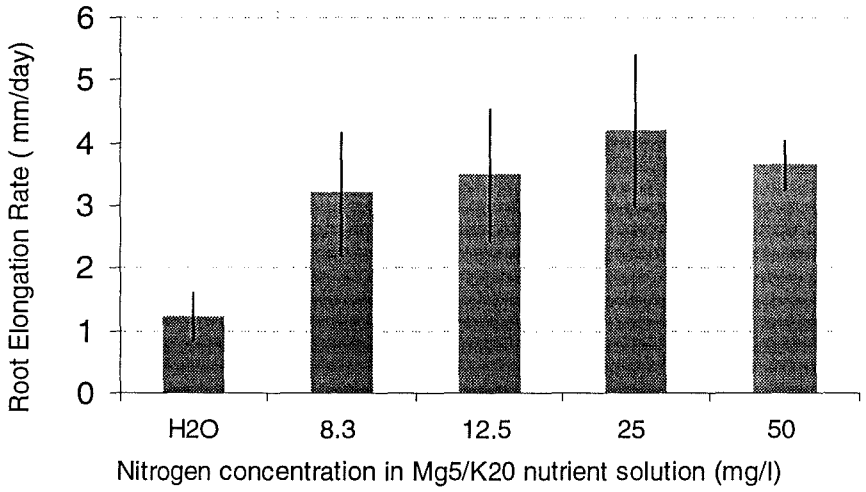


Figure A5.1. Relationship between Mg5/K20 nutrient concentration and root elongation rate (error bar is standard deviation)

Addition of Mg5/K20 nutrient solution into the rooting medium had a significant effect on the root growth compared with no Mg5/K20 nutrient solution addition treatment in the control ($p < 0.001$). However, there was no significant difference between the four nitrogen concentration treatments ($p = 0.67$). This suggests that the frequent nutrient solution replacement is successful in meeting the nutrient requirement of seedling growth. A Mg5/K20 nutrient solution with 8.3 mg/l nitrogen concentration can be used as the rooting medium for small radiata pine seedling cultures (less than one month old) when this solution is replaced frequently (every second day).

APPENDIX 6

SOIL STRENGTH MEASUREMENT EQUIPMENT: LABORATORY PENETROMETER

The soil strength of soil samples was measured using a laboratory penetrometer. This penetrometer was designed by Dr Rabi Misra (Faculty of Science, University of the Sunshine Coast, Australia) and manufactured by Precision Engineering Australia.

During penetration of the probe, the resistant force from the soil to probe is measured as a weight by the electronic balance beneath the soil sample. This weight then can be transferred into pressure based on the diameter of the probe.

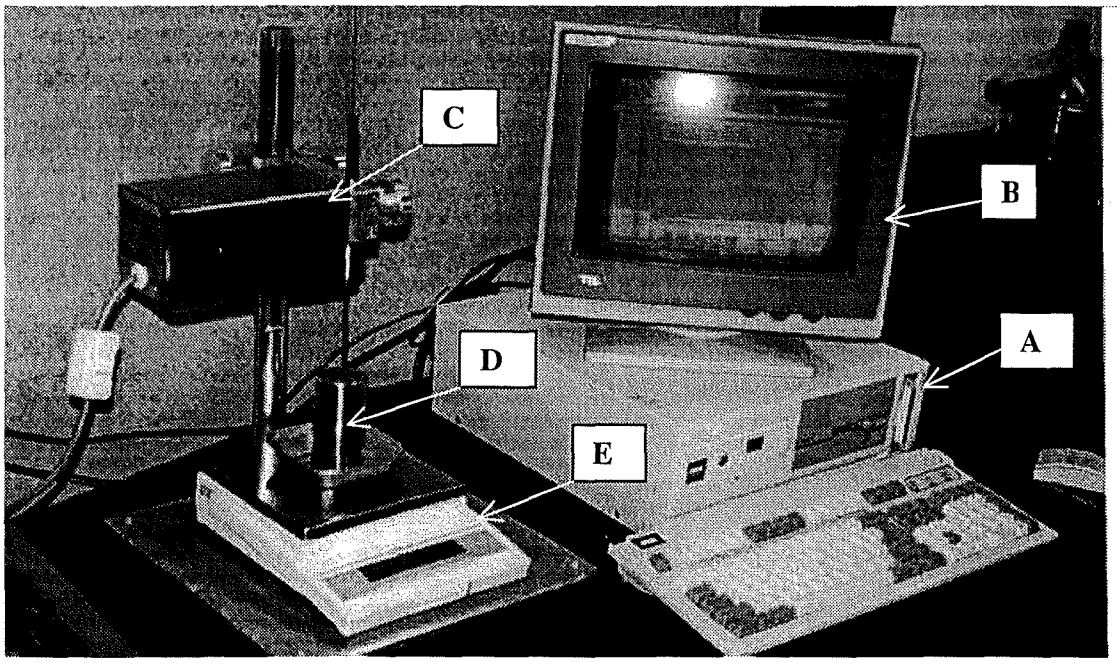


Figure A6.1.The laboratory penetrometer set-up, including an electronic balance and a computer compatible with software wedge for windows

A: Computer compatible with Software Wedge for Windows

B: Microsoft excel spreadsheet

C: Laboratory penetrometer

D: Soil sample

E: Sartorius BP 3100 S electronic balance (max 3100 gm, resolution 0.1 g)

The measured penetration resistance was downloaded into the Microsoft Excel spreadsheet using Software Wedge and a Microsoft Excel macro at a predefined time interval (10 seconds).

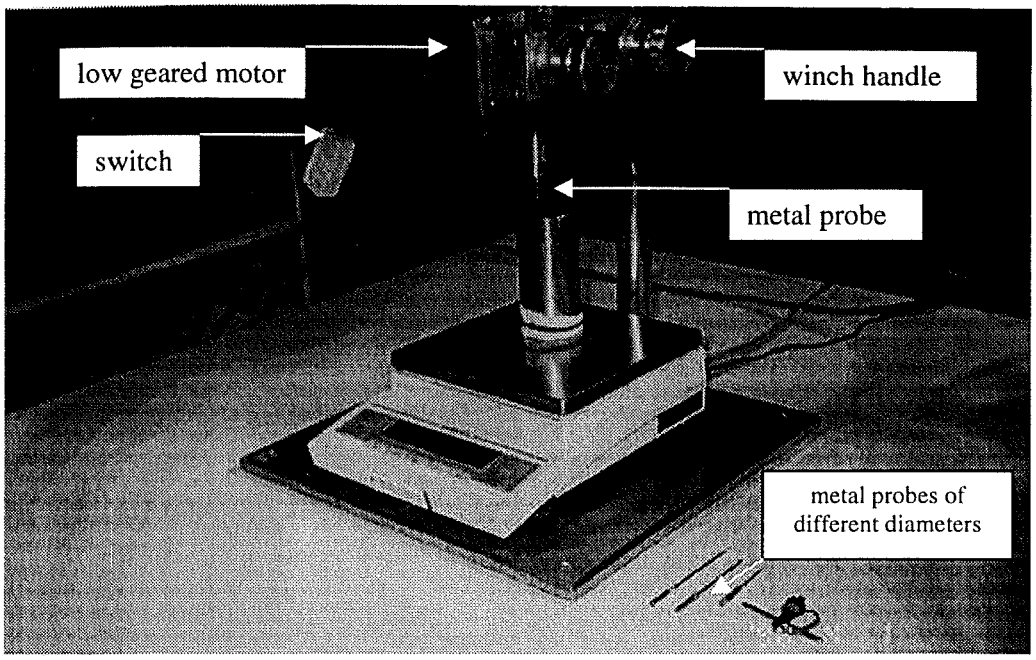
Measurement procedures:

1. The prepared soil sample was placed on the electronic balance and the weight was tared to zero;

2. The penetrometer was lowered so that the probe tip was nearly touching the soil surface; the soil sample was moved on the balance so that the point for soil strength determination was exactly under the probe tip;

3. The penetrometer was switched on and, as soon as the probe tip came into contact with the soil surface (ie. the electronic balance began giving a positive readout), software Wedge was activated. The recorded force by electronic balance was than automatically downloaded to the Microsoft Excel spreadsheet at the predefined time intervals;

4. After the probe reached the desired soil depth, the penetrometer was switched off first, and the probe was raised out of the soil sample and cleaned of any adhering soil before the next measurement.



Picture A6.2. Laboratory Penetrometer

APPENDIX 7

SAS OUTPUT FOR ROOT GROWTH MODEL

SAS Command

```
title equation3;
data new1;set new;
if avpot < -0.5 then delete;
proc nlin  data=new1;
parms a= 5, b=0.5, c=1;
model root = a*exp(-b*strength + c*avpot);
output out=pp p=pred r=resid;
proc gplot; plot resid*pred/vref=0; plot resid*strength/vref=0; plot resid*avpot/vref=0;
proc univariate plot normal; var resid;
run;
```

SAS Output

```
equation3          15:50 Saturday, June 26, 1999   1

Non-Linear Least Squares Iterative Phase     Dependent Variable ROOT       Method:
Gauss-Newton
              Iter       A             B             C        Sum of Squares
                 0       0.500000       0.500000       1.000000    3483.334408
                 1       9.379631      -0.104563      14.875829    1853.927638
                 2       7.997535       0.073644       5.573456     733.706068
                 3       8.627742       0.392013       0.875014     340.765200
                 4       9.256078       0.456009       1.698403     286.895455
                 5       9.368945       0.468136       1.757171     286.544431
                 6       9.370336       0.468661       1.754330     286.544033
                 7       9.370549       0.468658       1.754583     286.544031
NOTE: Convergence criterion met.

           Non-Linear Least Squares Summary Statistics  Dependent Variable ROOT

              Source                DF Sum of Squares     Mean Square

              Regression             3   3589.2883557    1196.4294519
              Residual             160    286.5440313       1.7909002
              Uncorrected Total    163   3875.8323870

              (Corrected Total)    162    858.1169612


              Parameter     Estimate    Asymptotic            Asymptotic 95 %
                                        Std. Error         Confidence Interval
                                                           Lower         Upper
              A          9.370548982 0.41267653027  8.5555452337  10.185552730
              B          0.468657726 0.03894435950  0.3917456731   0.545569778
              C          1.754582551 0.30038609961  1.1613435878   2.347821515
```

Asymptotic Correlation Matrix

Corr	A	B	C
A	1	0.5417766443	0.5415446797
B	0.5417766443	1	-0.209961533
C	0.5415446797	-0.209961533	1

equation3 15:50 Saturday, June 26, 1999 2

Univariate Procedure

Variable=RESID

Moments

N	163	Sum Wgts	163	100% Max	3.838088	99%	3.789841
Mean	0.005937	Sum	0.967804	75% Q3	0.90856	95%	1.930632
Std Dev	1.329945	Variance	1.768755	50% Med	0.025154	90%	1.558986
Skewness	-0.02665	Kurtosis	0.361201	25% Q1	-0.92238	10%	-1.60294
USS	286.544	CSS	286.5383	0% Min	-3.7652	5%	-2.04281
CV	22399.28	Std Mean	0.104169			1%	-3.60577
T:Mean=0	0.056998	Pr>|T|	0.9546	Range	7.603285		
Num ^= 0	163	Num > 0	82	Q3-Q1	1.830939		
M(Sign)	0.5	Pr>=|M|	1.0000	Mode	-3.7652		
Sgn Rank	55	Pr>=|S|	0.9277				
W:Normal	0.98671	Pr<W	0.8122				

Quantiles(Def=5)

Extremes

Lowest	Obs	Highest	Obs
-3.7652(	145)	2.50682(	73)
-3.60577(	5)	2.904687(	100)
-3.42023(	147)	2.933525(	117)
-2.65612(	146)	3.789841(	114)
-2.33057(	168)	3.838088(	96)

Missing Value	.
Count	8
% Count/Nobs	4.68

```
Stem Leaf                          #          Boxplot
   3 88                            2             0
   3                               
   2 5599                          4             |
   2 11                            2             |
   1 55555667888899                14            |
   1 0000001122333334              16            |
   0 555556667777778888999999      25          +-----+
   0 0001111222333444444           19          *--+--*
  -0 444333333322211111100         21          |     |
  -0 999999887776666665555         21          +-----+
  -1 44444333222211111100          20            |
  -1 998888665                     9             |
  -2 333100                        6             |
  -2 7                             1             |
  -3 4                             1             |
  -3 86                            2             0
     ----+----+----+----+----+
```

equation3 15:50 Saturday, June 26, 1999 3

Univariate Procedure

Variable=RESID